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INVESTIGATION OF THE MECHANISMS ASSOCIATED WITH GAS BREAKDOWN UNDER INTENSE OPTICAL ILLUMINATION

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I. SUMMARY

Under ONR Contract Nonr-4696(00), the Research Laboratories of United Aircraft Corporation are conducting experimental and theoretical investigations of the mechanisms which lead to gas breakdown by high intensity optical and infrared laser radiation. Experimentally, the radiation intensity required to produce the gas breakdown is obtained by focusing the output beam of a Q-spoiled laser. At sufficiently high power densities, the radiation causes the gas to become ionized and the resulting ionization greatly attenuates the subsequent portions of the laser pulse. The threshold or minimum power density required to generate gas breakdown has been studied as a function of gas species, gas pressure, radiation wavelength, and as a function of the volume, mode structure, and time history associated with the focused laser radiation. Studies were also made of the effects of partial preionization of the gas and of easily ionizable impurity atoms on the breakdown threshold. In addition, the expansion and development of the plasma generated by the radiation-gas atom interaction have been studied using high speed photography of the plasma luminosity and interferometric measurements of the plasma density and shock wave growth.

During the present report period, a high power Q-switched CO_2 laser with an output at 10.6 micron wavelength has been developed. Q-switched pulses with peak powers of 2×10^5 watts, a pulse duration of 10^{-7} sec, and pulse energies of 20 m joules at a repetition rate of 150 pulses per second are obtained from the oscillator-amplifier system developed. Using the output radiation of this laser, gas breakdown has been produced with 10.6μ radiation and studies made of the threshold power density required for breakdown as a function of argon gas pressure, gas species, and the volume associated with the focused laser radiation. The threshold value is compared with the optical frequency gas breakdown thresholds at $.6943\mu$ (ruby) and 1.06μ (neodymium), and is used to examine the frequency dependence of gas breakdown over an additional order of magnitude in frequency.

In part II, the results of the previous studies of gas breakdown by optical frequency radiation are described along with an outline of the high-power 10.6 micron Q-switched laser development and the gas breakdown studies carried out with this laser source in the present investigations. In part III, the cw and the Q-switched operation of the CO_2 gas laser are described in detail and the output power is examined as a function of the various laser parameters. In addition, in this section the operation of the CO_2 laser amplifier required for high power operation is also described. In Part IV, the measurements of gas breakdown with 10.6 micron wavelength radiation are presented and the experimental results obtained are compared with a theoretical model of the breakdown. Part V comprises a discussion of the present degree of understanding of the gas breakdown process, and a summary of the results obtained in the studies accomplished under this contract.

II. INTRODUCTION

The United Aircraft Research Laboratories under the sponsorship of the Office of Naval Research, Contracts Nonr-4299(00), Nonr-4696(00), and in a parallel corporate-sponsored program have been investigating the breakdown threshold of gases by optical frequency radiation, examining both experimentally and theoretically the mechanisms which cause gas breakdown (ionization) of gases under intense optical illumination. The experimental studies have been concerned with determining the threshold, i.e., the minimum power density required to ionize the gas as a function of gas species, gas pressure, volume within which the optical beam is focused, and radiation frequency. Studies of the effects of an initial preionization and the effects of impurity atoms in the gas have also been carried out, and the persistance and expansion of the plasma generated by breakdown has been examined using high-speed photography and Mach-Zehnder optical interferometry. A brief summary of the more prominant results are given below.

Using neodymium (1.06 micron wavelength) and ruby (0.69 micron) laser radiation, the dependence of breakdown threshold on gas species was studied. The threshold power density for argon, neon, and helium varied as the ionization potential divided by the collision frequency, in agreement with a cascade ionization process. Molecular gases such as air and nitrogen required somewhat higher power densities indicating that molecular gases, because of dissociation, vibrational excitation, or similar energy dissipation process, inhibit the breakdown development.

For all of the gases studied, the threshold power density is inversely proportional to the gas pressure from 7×10^3 torr, atmospheric pressure, to 10^4 torr. A minimum in the threshold as a function of pressure was observed in argon for breakdown produced within large focal volumes. This minimum occurred at 2×10^4 torr using neodymium radiation, and at 5×10^4 torr with ruby laser radiation. The threshold minimum was also observed for helium breakdown with neodymium laser radiation at a pressure of 5×10^4 torr. The classical cascade theory predicts a minimum in the breakdown threshold at the pressure where the electron-atom collision frequency equals the frequency of the radiation field. For argon and helium, this equality occurs at a pressure a factor of ~25 higher than that associated with the observed minimum. In Ref. 13, data are presented showing a minimum in threshold as a function of gas pressure, but the minimum occurs at higher pressures, apparently the result of the smaller focal volumes employed in those experiments.

Experiments were performed to determine the dependence of the breakdown threshold on the focal volume in which breakdown is initiated. The cylindrical focal volume is characterized by a dimension Λ, the diffusion length. The diffusion length for the long narrow cylindrical focal volume is approximately equal to the diameter of the focal spot divided by 4.8, and represents the characteristic dimension for particle diffusion from the volume. In all the gases studied, the threshold for breakdown was found to decrease with increasing Λ over a pressure range from 7×10^3 to 10^5 torr. In these experiments, Λ ranged from 1.6×10^{-3} to 3×10^{-2} cm, and the power density required for breakdown in the largest focal volumes was a factor of 100 lower than the threshold powers for the smallest focal volumes. The dependence of threshold on the dimensions of the focal volume indicate that a diffusion-like loss process may be controlling the threshold value. Such a loss process, which from the experimental results obtained dominates the breakdown development, is not accounted for by any existing theoretical model. Based on the results contained in this report, an alternative explanation of the observed dependence of threshold on Λ may be found in effects which lead to an enhancement of the radiation intensity within the focal region. In either case, the experimental observations are not fully understood and represents a serious discrepancy between the experimental results and theoretical models of gas breakdown with optical frequency radiation.

Studies of the threshold value in a Penning mixture (argon and neon) have shown that atomic excitation is a loss process in the development of breakdown. The addition of a small percentage of neon to argon reduced the threshold of pure argon by a factor of two and the dependence of the threshold on Λ was reduced in the gas mixture suggesting that radiation transport of atomic excitation energy is a diffusion-like loss process affecting the threshold value. In the argon-neon Penning mixture, an excited neon atom transfers its excitation energy to argon in a collision, ionizing the argon as a result of the near resonance of the excitation potential of neon and the ionization potential of argon. The reduced dependence of the threshold on Λ with the Penning mixture suggests that radiation transport of the atomic excitation energy inhibited by resonant radiation trapping is in part responsible for the volume dependence of the gas breakdown threshold. The results with the Penning mixture may also explain the reason for the higher breakdown thresholds of molecular gases; vibrational excitation of the molecules would introduce further losses in addition to atomic excitation and lead to the higher threshold values.

The frequency dependence of the gas breakdown threshold was obtained from a comparison of the data with ruby (0.69 micron wavelength) and neodymium (1.06 micron) laser radiation. At pressures below 10^4 torr, the higher frequency ruby radiation required larger power densities to produce breakdown than were required with neodymium laser radiation. At higher gas pressures the threshold values obtained with ruby and neodymium are comparable as a result of the minimum in the threshold as a function of pressure which occurs at a lower pressure with neodymium radiation than with ruby radiation. The frequency dependence of the gas breakdown threshold is in qualitative agreement with a cascade ionization process where the rate of energy addition is inversely proportional to the square of the radiation frequency.

For a cascade ionization process where the energy absorption is by free electrons colliding with gas atoms, an initial electron is required in the focal region to start the cascade process. Gas breakdown studies were carried out to examine the effects of an initial preionization in the focal region. Neodymium laser radiation was focused in a dc electrical dishcarge which provided the initial preionization. The threshold with the preionization was reduced by a factor of two below that of the gas without the dc discharge. Based on the initial electron density in the discharge, this reduction in threshold is in agreement with a cascade ionization process, and the results show that for breakdown with optical frequency radiation, the initial electron required to start the cascade process is readily available by some means and is not rate controlling in the breakdown development. The source of the initial electron is believed to derive from easily ionizable impurity atoms present in the test gas. Experiments were performed where small percentages of cesium was added to argon to test the effects of a low ionization potential constituent on the breakdown threshold. The threshold was reduced by the added cesium, showing that easily ionizable impurities can affect the breakdown development.

The photon energy of optical frequency radiation is 1-2 eV and only 10 or so photon interactions are required to ionize the inert gases or air. Because of the small number of absorptions required, the rate of energy gain may be greater than the rate for a process involving many photon interactions, as in the "microwave" absorption process. To test the effect of the relative size of the radiation photon energy and the atom ionization potential, gas breakdown in cesium vapor was studied using ruby and neodymium radiation. Cesium (ionization potential 3.9 eV) requires only 3 ruby or 4 neodymium photons of energy for ionization. From the experimental results, extrapolating the cesium breakdown data to atmospheric pressure and taking into account the difference in ionization potential and collision frequency, the breakdown threshold of cesium was found to be an order of magnitude lower than that of the inert gases, showing that the number of photons required for ionization is a significant factor in determining the breakdown threshold. The breakdown threshold of cesium with either ruby or neodymium radiation was the same, in contrast to the lower threshold for neodymium observed with the other gases. This result further demonstrated the importance of the photon energy-ionization potential ratio in the gas breakdown process.

The laser sources used in the gas breakdown experiments produce a multiple mode output, and the observed breakdown may be caused by large localized electric fields which result from interference between the various modes in the focal region rather than the temporally and spatially averaged field strengths measured experimentally. The effects of the mode structure of the laser beam on gas breakdown threshold have been examined using two radically different neodymium laser pulses: temporally smooth, multiple-mode laser pulses as used in the previous experiments, and mode-locked pulses with well-defined intensity spikes caused by phase locking of the laser cavity modes with a saturable dye Q-switch. The intensity fluctuations of the mode-locked pulses are more than a factor of 100 times the average power of the pulse train. Despite these large fluctuations, the average power density required for breakdown with the mode-locked pulse was found to be identical with that for the temporally smooth neodymium laser pulses. Based on these results, it was concluded that the breakdown threshold of gases by optical frequency radiation is independent of the mode structure of the laser radiation source, and the threshold value is adequately described by the temporally and spatially averaged intensities measured experimentally.

When gas breakdown occurs, an intense discharge is formed in the focal region and studies have been made of the persistence and growth of the breakdown plasma generated and of the effects of the plasma on the attenuation of subsequent laser pulses. At laser powers slightly above the threshold value, over one-half of the laser pulse energy is absorbed by the breakdown plasma, with instantaneous attenuations as high as 90 percent. The attenuation of the laser radiation persists for times as long as 100 nsec after breakdown initiation. A cw He-Ne laser beam transmitted through the breakdown region was severely modulated for times as long as several milliseconds after breakdown. This long time effect is due to refraction of the beam in the heated gas and shows that the transmission of subsequent laser pulses will be severely limited by these effects for more than a few milliseconds.

The blast wave generated by breakdown was studied using streak and framing photography of the luminous front. The luminous growth was observed to expand toward the laser focusing lens with velocities of the order of 10^7 cm/sec. Two mechanisms have been proposed to explain the rapid expansion: (1) a radiation-supported blast wave, and (2) a gas breakdown propagation where, as the incident power increases in time, the intensity ahead of the focus becomes sufficient to generate breakdown in the un-ionized gas. If the first of these mechanisms dominates the plasma growth, then the equilibrium temperature behind the blast wave can be calculated from the expansion velocity. With the second mechanism, the luminous growth is controlled primarily by the rise time of the laser pulse and the solid angle of the focusing lens, and thus is independent of the plasma temperature. The second mechanism has been observed to occur experimentally for breakdown with long focal length lenses. In these experiments, separate and distinct breakdowns were observed within the breakdown region in a time-position sequence similar to the luminous growth observed for breakdown with shorter focal length lenses. These results show that both mechanisms can be important in the plasma expansion, and further studies are required to determine whether the temperature of the breakdown plasma can be reliably evaluated from the breakdown expansion velocity.

Studies of the breakdown plasma and the blast wave produced by breakdown have been studied using a Mach-Zehnder optical interferometer. For times of one to two microseconds after breakdown initiation, the temporal and spatial growth of the blast wave as observed on the interferogram is described by the Taylor strong blast wave theory. Taylor's theory predicts the blast wave growth as

$$r = \left(\frac{\epsilon}{\rho}\right)^{1/5} t^{2/5}$$

where r is the radial position of the blast wave at time t, ϵ is the absorbed laser energy and ρ is the initial gas density.

The details of these results have been covered in the Final Report C-920088-2, under Office of Naval Research Contract Nonr-4299(00), the semiannual reports, C-920272-2, Dec. 1964; D-920272-4, Aug. 1965; E-920272-6, Jan. 1966), the Final Report E-920272-8, Aug. 1966, and the Semiannual Report F-920272-10, June, 1967, under Contract Nonr-4696(00). Further discussions of the observed phenomena have been reported in the open literature in Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, France, July 8-13, 1963; Physical Review Letters, Vol. 11, No. 9, November, 1963; Physical Review Letter, Vol. 13, No. 1, July, 1964; Proceedings of Physics of Quantum Electronics, McGraw-Hill Book Company, New York, 1966, p. 409; Physical Review Letters, Vol. 16, No. 24, June, 1966; and in Applied Physics Letter, Vol. 11, No. 3, August, 1967.

During this report period both experimental and theoretical studies of the cw and Q-switched operation of a CO_2 laser have been carried out with the goal of developing and using a high power radiation source for gas breakdown studies at 10.6 micron wavelength. The output of oscillator and oscillator-amplifier laser configurations has been examined as a function of the various experimental parameters of the laser system in order to optimize the operating conditions for maximum power output. Peak powers as high as 2×10^5 watts have been obtained from the Q-switched CO_2 laser. These power levels are sufficient to produce gas breakdown at the 10.6 micron wavelength. The breakdown thresholds for different gases at 10.6 microns are reported as a function of gas pressure, species and the focal volume. Using the breakdown thresholds obtained previously with the optical frequency lasers, the frequency dependence of gas breakdown is obtained over a range of laser wavelengths from 10.6 to 0.69 microns.

III. CO_2 LASER INVESTIGATIONS

The efficiency and output power of the cw CO_2 laser at 10.6 micron wavelength far surpasses those available from other laser systems. A mixture of CO_2, N_2, and He excited by an electrical discharge comprises the active medium of the CO_2 laser. Several kilowatts of continuous power have been reported[14] and efficiencies greater than 20 percent have been achieved.[15] Q-switching of the CO_2 laser has been accomplished but only moderate success has been achieved in coupling out the 10.6 micron radiation in the form of a high-power, Q-switched pulse.[12,16,17] In this section the development of a Q-switched CO_2 laser oscillator is described, along with a consideration of the conditions which limit the power obtained. The discussion of a high-power, oscillator-amplifier CO_2 laser system (output peak power $> 10^5$ watts) completes this section.

On the basis of an elementary analysis, the pulse peak power available from a Q-switched CO_2 laser oscillator is quite large[18]. As will be discussed, however, the dynamics of the energy storage and transfer in the CO_2 laser requires modifications on this simple theory and leads to significantly lower output powers. If R is the net rate of population inversion of the CO_2 laser, then the maximum power obtainable in cw operation is

$$P_{cw} = Rh\nu \tag{1}$$

where $h\nu$ is the energy of the laser transition. In Q-switch operation, the optical cavity is initially unaligned and the population inversion in the medium accumulates for a time equal to the relaxation time of the upper laser level, τ. The stored energy is then $Rh\nu\tau$, and the maximum Q-switched laser power is

$$P_Q = \frac{Rh\nu\tau}{T} \tag{2}$$

where T is the pulse width, determined primarily by the cavity length and the method of optically coupling the power out of the laser cavity. Thus, the maximum ratio of Q-switched to cw power is

$$P_Q / P_{cw} = \frac{\tau}{T} \tag{3}$$

For the CO_2 laser the relaxation time, τ, is of the order of 10^{-3} sec,[19] and experimentally the pulse width can be as short as 10^{-8} sec giving a P_Q / P_{cw} ratio of 10^5. On the basis of this analysis a 100 watt cw laser can produce Q-switched pulses of 10^7 watts. However, this analysis evaluates only the maximum Q-switched power which can be obtained and does not take into account the energy transfer and relaxation of molecular transitions which while operative on a cw basis are too slow to contribute to the Q-switched laser output.

The CO_2 10.6μ laser output occurs on the molecular transition from the asymmetric vibrational 001 state to the symmetric bending 100 level. Associated with both the levels are a series of rotational states, and the laser output consists of a number of vibrational-rotational transitions closely grouped about 10.6 . A few of these possible transitions generally exhibit higher gain than the others, and these few dominate the laser output. In the discharge, nitrogen molecules are vibrationally excited in near resonance with the CO_2 001, 002, ..., 00n asymmetric vibrational modes and by resonant energy exchange collisions populate the upper CO_2 laser level and the CO_2 higher vibrational modes. Helium in the discharge serves to depopulate the 100 lower laser level giving a higher population inversion. In cw operation, the upper CO_2 vibrational levels, (002,...,00n) are collisionally coupled to the 001 level and enhance the cw power output. For the laser discharge pressures generally used, the relaxation time for the 00n → 00n-1 collisions is of the order of 10^{-6} seconds. The rotational levels of the 001 are more closely coupled with relaxation times of the order of 10^{-7} seconds. Thus, for cw operation, collision processes will continuously repopulate the dominant upper laser levels at a rate faster than the excitation of the CO_2 by vibrationally excited N_2 for which the relaxation time is 10^{-4} sec. Thus, for all of the stored energy utilized in cw operation to be available in Q-switched output, the pulse duration must be greater than 10^{-6} sec. From Eq. 3, therefore, the ratio of the Q-switched to the cw power can be no larger than 10^3. For pulse widths less than 10^{-6} sec, the energy stored in the CO_2 upper vibrational levels (002,...,00n) is not available for laser action since it cannot be transferred to the 001 upper lasing level during the pulse. Thus, a reduction in pulse width below 10^{-6} sec is accompanied by a decrease in pulse energy and may not result in increased power output. For pulse widths below 10^{-7} sec, however, the energy available is that stored in the particular vibrational-rotational upper laser levels involved in the laser action and does not involve any energy transfer collisions. As a result a decrease in the pulse width will give increased pulse power; however, since the laser pulse width experimentally cannot be reduced much below $\sim 10^{-7}$ sec, the optimum value of P_Q/P_{cw} appears to be limited to $\sim 10^3$.

For visible wavelength lasers, electro-optical shutters involving Kerr cell or Pockel's cell elements have been successfully used for rapid Q-switching of the optical cavity. These systems are not applicable for Q-switching of CO_2 lasers because of the large absorption of the Kerr fluid or Pockel's crystal at 10.6μ . Saturable absorbers which operate at 10.6μ have been found but these have not led to high peak powers.[12,17] The technique which has proved most successful is a rotating mirror Q-switch and is employed in these experiments. In the course of the high power Q-switched laser development, operation of the system was studied with both dc and pulsed electrical discharge excitation in cw and with both dc and pulsed electrical discharge excitation in cw and Q-switched mode. The results of these studies, as they contributed to an understanding of CO_2 laser operation and led to the high-power, Q-switched system used in the breakdown experiments, are discussed in this section.

A. CW CO_2 Oscillator

A schematic drawing of the CO_2 laser oscillator is shown in Fig. 2. The discharge tube is a one-inch diameter pyrex pipe enclosed within a water jacket for cooling of the tube. The optical cavity is formed by a flat partially reflecting output mirror and a ~100 percent reflectivity mirror with a large radius of curvature (6.78 meters) spherical reflector. The use of a spherical reflector greatly reduces the critical alignment requirements of a flat-flat cavity. For Q-switching, a flat variable speed rotating mirror is situated in the optical beam between the two cavity mirrors as shown in Fig. 2. By placing the rotating mirror within the cavity, alignment is accomplished with the two accessible stationary mirrors, and the multiple reflection serves to double the effective mirror rotational rate. A polished sodium chloride flat mounted at the Brewster's angle is used to seal one end of the discharge tube and the partially reflecting output mirror is attached directly to the other end of the tube to eliminate a second window in the laser cavity. Various partially reflecting mirrors and hole coupled gold coated mirrors were tested for output coupling. Optimum operation was obtained with a flat dielectric coated Irtran II partially reflecting mirror with a reflectivity at 60 percent. In cw operation the rotating mirror was fixed in position and the cavity mirrors adjusted for maximum output. For excitation, a constant voltage dc power supply was used with a ballast resistor in series with the discharge tube. The ballast resistor, whose resistance is comparable with the impedance of the discharge, is required to offset the negative voltage-current characteristics of the discharge tube and thus permit stable operation of the laser. The oscillator employs a flowing gas system pumped with a 400 l/min pump and the partial pressures of the several constituents are determined from variable area flow meters and the total pressure in the discharge. Optimum operation is obtained with 80 percent helium, 12 percent nitrogen, and 8 percent CO_2 at a total pressure of 12 torr, and a discharge current of 50 milliamperes, with the voltage depending on the length of the discharge. Plotted in Figs. 3-5 is the power output of a one-meter oscillator as a function of the partial pressure of the different gases. For these curves, the discharge current was maintained at a constant value and the partial pressure of the other two gases were fixed at their optimum values. From these curves, for maximum power output the partial pressure of CO_2 is the most critical while the variation in power with helium pressure is the least sensitive. The output power of the cw oscillator was examined as a function of discharge current with the results shown in Fig. 6. The laser power increases with increasing current up to 50 milliamperes with a slight decrease in power for higher currents. The output powers are lower than those reported in the literature as a result of the sodium chloride window within the cavity and the three mirror cavity configuration. The three-mirror cavity was required for Q-switching and to provide a basis for comparison was also used for the cw oscillator investigations. An output power of 30 watts was typically obtained with the one-inch diameter, one-meter long oscillator although care in alignment and selection of the optical components, cw powers as high as 50 watts could be produced. The oscillator discharge was varied in length from one meter to five meters and the cw power output was observed to scale linearly with length. On the basis of this result, the cw laser is operating in a saturated condition and from the data the saturation power density is approximately 20 watts/cm^2. Two-inch diameter pyrex tubing was also used for the discharge. For equal discharge tube lengths the cw power obtained with this larger diameter tube was identical with that of the one-inch diameter tube, while the CO_2 partial pressure for optimum output power was reduced by a factor of two. The presence of the discharge tube walls is therefore important in determining the conditions within the discharge, and experimentally for maximum cw output power, the product of the CO_2 and the tube diameter is a constant.

B. Pulsed Electrical Discharge CO_2 Laser Oscillator

To determine whether pulsed discharge excitation of the laser medium would result in an alteration of the electron distribution function and lead to more efficient pumping of the laser, operation of the laser oscillator was investigated with a capacitor voltage source replacing the dc power supply. Pulsed excitation, in addition to altering the discharge conditions, would also reduce the thermal heating of the discharge tube reducing the population of the lower laser level and thus increase the inversion of the medium.

A schematic of the laser system for pulsed operation is shown in Fig. 7. The one-microfarad, 25-kilovolt capacitor is triggered by a spark gap in series with a 2½-meter long discharge tube. The current is limited by the impedance of the discharge as well as a variable ballast resistor in series with the discharge tube. Plotted in Fig. 8 is the peak power of the laser output pulse obtained with this system as a function of the maximum current through the tube, determined by the ratio of the capacitor voltage to the ballast resistor. Since the discharge impedance is not zero, the true current in the discharge will be somewhat lower than the values of Fig. 8. With a ballast resistance of 25,000 ohms, the power output was a maximum, 700 watts, and this compared with the optimum cw power of 125 watts shows that pulsed operation does permit higher power laser output for a given discharge length and medium composition.

C. Q-Switched CO_2 Laser Oscillator

To increase the peak power output of the laser, the dc electrical discharge oscillator was Q-switched with a rotating mirror using the three-mirror system shown in Fig. 1 and described in Section A. Passive Q-switching of the CO_2 laser was investigated using various gases which have strong absorption bands at 10.6 microns. The results, reported in the previous progress report[12] showed that Q-switching with the absorbing gases was obtained but the peak power of the resulting pulses was not as high as obtained with the rotating mirror. For the rotating mirror, a two-inch diameter gold flat was mounted directly on a variable speed grinding motor giving rotational speeds up to 250 cycles per second without excessive vibration. With the three-mirror system the effective rotational speed of the mirror is double this value. The rotating mirror is deliberately misaligned with respect to the output mirror so that the optical cavity is formed only by the three-mirror system thus producing only one pulse per rotation. Studies were made of the Q-switched laser output for discharge tube lengths from one to five meters and tube diameters of one and two inches. To avoid reflections from the discharge tube walls, which as discussed in the earlier report,[12] result in laser action for off axis alignments of the rotating mirror and thus reduce the peak power of the Q-switched pulses, the tube walls were frosted with an acid solution. The frosting greatly reduced the emission prior to the giant laser pulse but did not eliminate it entirely for the longer length oscillator system because of the reduced angle of internal reflection and increased overall gain. No appreciable difference in Q-switched output or pre-pulse lasing was observed for the one- and two-inch discharge tube diameters.

Typically the Q-switched output of the laser consists of two pulses whose peak amplitudes are separated by 1 microsecond. For example, with a $2\frac{1}{2}$-meter long, one-inch diameter discharge tube, and a 60 percent reflectivity output mirror, Q-switched output pulses as shown in Fig. 9 were obtained for a rotational speed of 150 cps and were not altered for changes in rotation rate by a factor of 2. Twenty-five successive pulses are shown superimposed demonstrating the reproducibility of the laser system. Since the pulse separation is essentially independent of mirror rotation rate, the double pulsing apparently results from the dynamics of the laser medium. In cw operation, once the 001 upper laser level is depopulated, either by collisional de-excitation or by laser action, the higher 002,...,00n levels of CO_2 repopulate it with a relaxation time of 10^{-6} sec. The repopulation is effected by energy exchange collisions since the radiative lifetime of the $00n \rightarrow 00n-1$ transitions are $\sim 10^{-2}$ sec, much slower than the collisional relaxation at the normal operating pressures of the CO_2 laser. In Q-switched operation, however, depopulation during the pulse occurs at a rate greater than the collisional relaxation time and the medium gain can be depleted. Subsequent repopulation of the upper laser level by collisions can again produce an inverted population resulting in a second output pulse. To examine this effect and determine whether this phenomenon is responsible for the observed double pulsing, experiments were performed to measure the effects of discharge pressure on pulse separation. The results of these experiments are shown in Fig. 10. Plots of pulse separation as a function of discharge pressure are shown in the figure for two discharge currents. In each case, above ~ 8 torr as the pressure of the discharge is decreased, the time between pulses increases and $1/t$ is approximately linear with pressure as expected for a collisional de-excitation process. At the lowest pressures, with decreasing pressure the time between pulses increases, apparently as a result of the decrease in overall gain of the laser system below 8 torr.

In a similar fashion, the rotational structure of the CO_2 vibrational levels affects the Q-switched output. Dipole transition selection rules dictate that only transitions between particular rotational levels of the upper and lower laser states can occur. In general, the discharge conditions in the CO_2 laser are such that the gain is sufficiently high for laser action for only a limited number of the allowed transitions and the output of the laser consists of only these few rotational transitions. The other rotational levels, however, thermalize by collisions and repopulate the rotational levels depleted by lasing. This relaxation is important in cw operation and contributes significantly to the total energy available for lasing. However, the thermalization time for rotational equilibration is of the order of 10^{-7} sec and in order to use the energy stored in all of the rotational levels, the Q-switch pulse length must be of the order of 10^{-7} seconds. This relaxation time sets a lower limit on the Q-switched pulse width for which optimum energy is obtained. For shorter times, the energy is reduced approximately as the ratio of the pulse duration divided by 10^{-7} sec and no gain in peak power is achieved. Experimental confirmation of these considerations is given by the fact that the optimum power from the Q-switched oscillator is achieved for pulse widths of 2×10^{-7} seconds, and while shorter pulses can be produced, the pulse energy is also reduced resulting, in fact, in lower peak powers.

With a $2\frac{1}{2}$-meter long Q-switched oscillator, the pulse peak powers obtained were 10-20 kilowatts and $\sim 2 \times 10^{-7}$ sec duration. Laser pulses at this power level were insufficient to produce gas breakdown even when focused in gases at pressures as high as 10 atmospheres. Because of the difficulties of maintaining optical alignment and the increased effects of pre-pulse lasing with the longer oscillator systems, a short oscillator coupled with a long amplifier system was considered the most promising approach to achieve the power levels necessary for gas breakdown.

A one-meter long, one-inch diameter Q-switched CO_2 laser was selected as the oscillator portion of the system and experiments were carried out to determine the optimum conditions of discharge current and gas mixture for optimum pulse shape and peak power. Figures 11 to 13 show the peak Q-switched power as a function of the partial pressure of the various gases. The dependence of the peak power on nitrogen and helium pressure is similar in form to that of the cw oscillator output, Figs. 4 and 5. However, compared with the results of Fig. 3 for the cw oscillator, the Q-switched power output is relatively insensitive to CO_2 pressure over the range from 0.5 to 2.0 torr. At low partial pressures of nitrogen, the double pulses obtained when the Q-switched laser is operated at the pressures which give optimum cw output were not observed. The output at these pressures consisted of a single pulse whose power was comparable to the double pulse peak power. Although the peak power as a function of discharge current is not shown in a figure, it was observed experimentally that the current at which optimum power was obtained was significantly lower than the optimum current for cw operation. This may result from the fact that under cw conditions the power removed from the discharge by lasing is significant while in Q-switching operation this power must be dissipated by conduction to the walls and results in increased heating of the gas. This heating serves to increase the population of the lower laser level reducing the population inversion and gain; a more optimum balance between excitation and lower laser level population is apparently obtained at lower currents in the Q-switched system. In Fig. 14 is shown the Q-switched oscillator power as a function of total discharge pressure. In these experiments, the optimum gas mixture determined from Figs. 11 to 13 was employed in the oscillator. As the discharge pressure is increased, the energy per pulse remains essentially constant, although the pulse duration decreases resulting in a higher power output from the laser. The decrease in pulse width with increased pressure is indicative of the effects on the Q-switched laser operation of the collisional relaxation processes discussed above. Above 13 torr, the laser power is approximately constant up to pressures of 20 torr, the highest pressure examined in the experiments. In this pressure range, the peak powers obtained from the Q-switched, one-meter long oscillator were typically 8-10 kilowatts.

D. Q-Switched Pulsed Electrical Discharge CO_2 Laser

To examine the effects of the increased cw power available from the pulsed electrical discharge laser on the Q-switched pulse output, the pulsed discharge laser described in Section B was Q-switched with a rotating mirror synchronized with the electrical pulse. The energy obtained per pulse was indeed increased to 5-7 millijoules compared to the 1-2 millijoules obtained with the dc excited discharge Q-switched laser. This energy increase is very close to the factor of ~ 4 power gain observed between the cw and pulse excited laser. However, measurements of the pulse width carried out during this report period showed that the Q-switched pulse widths were from 3 to 4 times longer than the pulse widths of the dc discharge Q-switched laser giving comparable peak powers for the two systems. Apparently in the pulsed discharge system, the power increase over the cw laser is the result of excitation of higher lying CO_2 vibrational states. These states relax in a time of ~ 1 microsecond, adding to the energy of the non-Q-switched pulsed system. In Q-switched operation, however, the energy in these higher lying states becomes available only as relaxation occurs to the upper laser level. As a result, gain is maintained over a longer time giving a pulse with more energy but of longer duration and with no increase in peak power. Because of the experimental difficulties of synchronization of the Q-switched mirror with the pulse discharge excitation and since no increase in power was obtained with this system, the Q-switched dc excited electrical discharge laser was employed as the oscillator for a high power oscillator-amplifier system.

E. CW CO_2 Laser Amplifier

To examine the characteristics of CO_2 laser amplifier operation, experiments were first performed to determine the amplification of a cw oscillator beam for different conditions of gas pressure, amplifier length, and gas flow. The laser amplifier for these experiments consisted of a two-inch diameter pyrex tube encased, like the oscillator tube, within a water cooling jacket. DC excitation of the discharge was effected in the flowing gas between electrodes at each end of the amplifier tube, as shown in Fig. 15. Beam path lengths from $2\frac{1}{2}$ to 10 meters in the amplifier were employed. For the 5 and 10 meter path lengths, the beam was passed twice through respectively a $2\frac{1}{2}$ and 5 meter long amplifier system. A Brewster angle polished NaCl flat formed the input window to the amplifier, and for the double pass configurations the flat NaCl output window was replaced with a 6.78

meter radius of curvature mirror returning the beam back through the amplifier discharge. The pumping capacity for the amplifier was 400 liters/min with the $2\frac{1}{2}$ meter length and was increased to 800 liters/min for the experiments with the 5 meter length discharge tube. The cw amplification was linear with amplifier length, with a gain of 0.5 percent per centimeter. To eliminate the effects of any losses associated with the amplifier optics and alignment, the gain of the amplifier was determined from measurements of the system output power with and without the amplifier discharge, but in each case with the oscillator beam passing through the amplifier section. The increased gas flow resulting from the use of a 4000 liters/min pump resulted in no appreciable increase in gain. The amplifier output was examined for different pressures of the active gases, and the optimum gain was observed to occur at the same partial pressures as for maximum output from a two-inch diameter cw oscillator. For cw operation, the oscillator-amplifier system gave a lower power output than a simple oscillator of the same total discharge length. The main advantage of the amplifier, however, is for Q-switched operation and is described in the following section.

F. Q-Switched CO_2 Laser Amplifier

Although the laser oscillator-amplifier system offered no advantage over a simple oscillator for cw operation, this configuration was also examined in Q-switched mode to determine whether the increased peak power required for the gas breakdown studies would be obtained. The 1 meter long Q-switched oscillator described in Section C was employed in these investigations. With $2\frac{1}{2}$ to 5 meter beam paths in the amplifier discharge, both the power and energy amplification of the pulse were linear with length. Increasing the amplifier path length to 10 meters, however, resulted in considerably more than a linear increase in both the energy and power amplification, as indicated by the results tabulated in Table I. In addition to discharge tube length, the gas flow rate through the amplifier - i.e., experimentally, the pumping capacity employed on the amplifier -

TABLE I

Amplifier Length (Meters)	cw Power Amplification	$\frac{\text{T oscillator}}{\text{T oscillator-amplifier}}$	Q-Switched Energy Amplification	Q-Switched Power Amplification
$2\frac{1}{2}$	1.25	0	1.25	1.25 +
5	2.5	0	2.5	2.5 +
10	5.0	1/2	8	16 ‡
10	5.0	1/2	12	24 *

+400 liters/minute pumping capacity
‡800 liters/minute pumping capacity
*4000 liters/minute pumping capacity

had a significant effect on the Q-switched pulse amplification. In particular, with the 10 meter amplifier discharge length, the pulse peak power was increased by 50 percent on changing the pumping capacity from 800 liters/min to 4000 liters/min, although in cw operation the amplification was not effected by the increased pumping capacity. An energy amplification of 12 (approximately one percent per cm) was obtained with the 10 meter path amplifier using the 4000 liters/min pumping rate. The power amplification, however, was a factor of two greater, or 24 times, as the result of a reduction by a factor of two in the total width of the amplified pulse. This pulse shortening is shown in Fig. 16 as it develops with increasing amplifier gas pressure. As the discharge pressure (and from Fig. 17 the gain of the amplifier) is increased, the first pulse of the oscillator double pulse is amplified successively more than the second until the output appears as only a single pulse shortened to 100-150 nanoseconds width. Although not shown in a figure, over the same pressure range the energy amplification is essentially linear. It appears, therefore, that the amplification of the leading edge of the oscillator double pulse in the amplifier depletes the available inverted population reducing the gain for the second pulse. While in the oscillator repopulation of the upper laser level by collisions occurs in $\sim 10^{-6}$ sec giving rise to the second pulse $\sim$ 0.5-1 μsec later. With the available power supply, however, the long amplifier discharge could be operated at pressures only up to 6 torr, approximately $\frac{1}{2}$ the 12 torr oscillator discharge pressure. As a result, the relaxation time in the amplifier is about twice that in the oscillator, and repopulation of the upper laser level in the amplifier does not occur until after the oscillator pulse. Consequently, the second pulse of the oscillator output is surpressed and a single output pulse is obtained from the amplifier. Since, from the results of Fig. 16, amplification of the first pulse of the oscillator output results in depletion of the upper laser level, at the highest amplifier pressure the amplifier operation is saturated. In addition, the high electric field intensity of the high power beam can Stark broaden the rotational states of the upper laser level, increasing the population of molecules available for amplification of the oscillator output. In normal operation the rotational levels are only 50 Mcs wide but are separated by 55 Gcs. Since the rotational relaxation time is $\sim 10^{-7}$ sec, adjacent levels cannot repopulate a depleted rotational level during the Q-switched pulse. Stark broadening by the electric field of the amplified beam is sufficient to cause the neighboring rotational levels to overlap the upper laser level. This increases the effective upper state population and thus the gain of the amplifier and along with the saturation effects could account for the more than linear increase in energy gain of the 10 meter path amplifier as compared with the 5 meter system. In addition to the effects of saturation, the pulse shortening may also be related to the π-pulse phenomenon associated with the propagation of a high-intensity radiation pulse in an amplifying medium.[20] Using the 10 meter path amplifier, studies of the amplification of the Q-switched oscillator pulse as a function of the discharge current, relative gas pressures in the discharge, and total pressure were carried out with the results shown in Figs. 17-21. From Fig. 21, the amplifier performance is relatively insensitive to discharge current from 25 to 50 milliamperes, although at higher currents the output is decreased. The dependence of the amplifier output on gas partial pressure, shown in Figs. 18, 19, and 20, for nitrogen and helium is similar to that obtained with the Q-switched laser oscillator. The CO_2 pressure, however, is critical to optimum operation of the amplifier, similar to the result obtained for the cw laser oscillator. With the amplifier operating at the optimum constituent partial pressures as determined from Figs. 18, 19, and 20, the amplifier performance was also examined as a function of total gas pressure with the results shown in Fig. 17. The increase in performance as the total pressure was increased from 2 to 4 torr is the result of the pulse shortening discussed above and is not well understood at this point.

In summary, a high-power, Q-switched CO_2 laser has been developed and studies have been made of the oscillator under cw and pulsed electrical excitation. The Q-switched powers of 10-20 kilowatts have been achieved from the oscillator, the peak power limited by the relaxation times associated with CO_2 molecular transitions, and, with long oscillator discharge lengths, mechanical problems of mirror alignment and pre-pulse lasing associated with reflections from the tube walls. The amplification of the Q-switched output pulses from the CO_2 laser oscillator has been examined for CO_2 laser amplifiers up to 10 meters in length. With the 10 meter amplifier path length, the oscillator pulses were amplified in energy by a factor of 12 and shortened in duration by a factor of 2, resulting in a power amplification of 24. The amplification of a cw beam by the same system was only a factor of 5. Peak pulse powers of 200 kilowatts have been obtained with this oscillator-amplifier CO_2 laser system. These powers are a factor of 10 greater than any published for a Q-switched CO_2 laser. The 200 kilowatt peak power 10.6 micron wavelength pulses obtained with this system were sufficiently intense to produce breakdown in argon, xenon, and helium, and gas breakdown experiments carried out with the 10.6 micron radiation are described in the following section of this report.

IV. GAS BREAKDOWN STUDIES WITH 10.6 MICRON CO_2 LASER RADIATION

Using the > 100 killowatt peak power Q-switched pulses of the oscillator-amplifier CO_2 laser described in the previous section, studies have been made of the breakdown or ionization threshold of gases at 10.6 micron wavelength radiation and the results obtained compared with those of previous investigations under this contract at optical and near infrared frequencies with ruby and neodymium laser radiation. The data extends the frequency dependence of gas breakdown studies over a range previously inaccessable before the development of the Q-switched laser described in the previous sections. The dependence of the breakdown threshold on the volume associated with the focused radiation was measured in atmospheric pressure argon, and the threshold for breakdown by CO_2 laser radiation was determined as a function of gas species for argon, helium and xenon. A high pressure cell was used to study the dependence of the argon breakdown threshold on gas pressure from atmospheric pressure to 7 atmospheres of argon, the pressure limited by the mechanical strength of the infrared transmitting windows and lenses presently available. Power levels up to 200 killowats were insufficient to produce breakdown in air, even at pressures as high as 7 atmospheres.

To determine the laser pulse power density for the breakdown threshold studies, the energy and time duration of the CO_2 laser pulse and the size of the focused laser beam were measured experimentally. Two techniques were used for measuring the pulse energy. In the first, the average power output of the Q-switched laser was determined and the average energy per pulse calculated from this power and the pulse repetition rate, experimentally the Q-switch mirror rotation rate. For the second technique, a camera shutter, open for a time shorter than the pulse repetition rate, was used to select a single pulse whose energy was then measured with a ballistic thermopile. Both techniques give the same energy per pulse, ~15-20 millijoules at the highest powers, and show that variations in energy of the individual Q-switched pulses are small. The envelope waveform of the pulses was measured with a gold doped germanium detector cooled to liquid nitrogen temperature. The detector had a response time of 2×10^{-8} seconds, sufficiently fast for observing the shape of the 10^{-7} second duration laser pulses. To determine the laser focal spot size, divergence of the laser beam was measured from the burn image produced on exposed polaroid film at the focus of a long focal length lens. The laser radiation was attenuated until the threshold of damage to the film was obtained. Increasing the beam power by 50 percent above this threshold, the size of the resulting burn spot gives the half power width of the beam. From geometrical optics, the diameter of this focal spot divided by the lens focal length is the full angle half power divergence of the laser beam. Using lenses with focal lengths from 25 to 6.5 cm, the full angle beam divergence, θ, was measured and is

$$\theta = 3.6 \times 10^{-3} \text{ radians,}$$

only 1.8 times larger than the 2×10^{-3} radians diffraction limited divergence for a two cm diameter beam at 10.6 micron wavelength.

Using the output pulse from the 100 kilowatt oscillator-amplifier CO_2 laser, gas breakdown has been produced in argon, helium, and xenon; under no experimental conditions was breakdown obtained in air even at 10 atmospheres pressure. Breakdown was easiest to produce in argon and xenon, and because of its greater availability at higher pressures, argon was employed for the pressure, frequency, and volume dependence measurements. Even with argon, breakdown was not observed for every pulse at the lower pressures and it was necessary to modify the criterion for breakdown for the investigations of the different dependences. As a result, while the thresholds obtained in each case are given in watts/cm^2, they should be used only to determine the variation of the threshold as a function of the parameter under study and not compared between different experiments.

The breakdown luminosity, observed visually is approximately 1/2 cm long and very intense, similar in appearance to the gas breakdown obtained with optical frequency radiation. The size and intensity of the breakdown is unexpected since in the optical frequency experiments nearly one joule of energy is absorbed by the gas while the total energy of the 10.6 micron radiation pulses is only 2×10^{-2} joules. Breakdown was not always observed with every pulse even at high gas pressures. To facilitate breakdown, a Tesla spark coil was used to preionize the gas in the focal region of the lens used to focus the laser radiation. After this treatment, continuous breakdown with each pulse was observed even without the Tesla spark. Upon attenuation of the laser beam the intense breakdown spark was eliminated, but close examination of the focal region showed small, minute sparks in the focal region. A photograph of the gas breakdown luminosity and of the low intensity lumonisity associated with the minute sparks are shown in Fig. 22. The intensity of the breakdown is very much greater than that of the luminous glow. A one minute exposure of the film was required to photograph the glow shown in Fig.22 , while the breakdown photograph is of a single breakdown plasma which lasts only for a few microseconds. These small, minute sparks are present at low power levels (10-20 kilowatts), while the intense breakdown sparks require a definite threshold, or minimum power density, for their formation. It appears that the small sparks are derived from impurities in the gas, and as will be discussed later, may provide the initial ionization for the ionization cascade which leads to breakdown by the high intensity laser pulses.

From the results of the measurements of the breakdown threshold in a preionization gas discharge reported in Ref. 5, an initial ionization of the order of 10^{11} cm^{-3} or more is required to reduce the threshold by as much as a factor of two. From the intensity of the luminosity of the minute sparks, however, the electron density produced is estimated to be significantly less than this value. As a result, the threshold value obtained with the impurities present should still provide a valid measure of the cascade threshold. Power densities three or four times as large as those determined in this fashion would not cause breakdown in gases of higher purity. It therefore appears that at 10.6 microns the production of the initial ionization is rate limiting in the breakdown of pure gases while at optical frequencies the initial ionization was apparently readily produced at the power levels required for the ionization cascade.

A. Pressure Dependence of Gas Breakdown Threshold at 10.6 Microns Wavelength

For measurements of the pressure dependence of the 10.6 micron gas breakdown threshold, a high pressure cell was used with a 2.5 cm focal length, 1.2 cm aperature Irtran II lens forming the entrance window of the cell. The mechanical strength of the lens limited the maximum cell pressure to 10 atmospheres. A camera shutter was used to select and transmit a single pulse from the repetitive pulse output of the laser, and the single pulse breakdown threshold of argon was determined at 7 and 4 atmospheres of pressure. For the measurements of the breakdown pressure dependence, the breakdown threshold was defined as that laser beam power density at the lens focus such that 10 successive separate pulses would not produce a breakdown plasma. The threshold values obtained are given in Table II. The pressure range over which data could be taken was limited at high pressures by the strength of the infrared lens and at low pressures by power output of the laser system. From the data obtained, however, it is observed that the threshold power density is decreasing approximately linearly with pressure and is in agreement with a loss-free cascade breakdown development as discussed in a later section of this report.

Table II

Argon Breakdown Threshold vs. Pressure

Argon Pressure	Breakdown Threshold (watts/cm^2)
7 atms	0.6×10^9
4 atms	1.1×10^9

B. Frequency Dependence of Gas Breakdown

Comparison of the 10.6 micron breakdown threshold with the values obtained at 0.6943 microns and 1.06 microns with ruby and neodymium laser radiation respectively, extends the evaluation of the frequency dependence of breakdown over an order of magnitude in frequency from 1.8×10^{14} to 3×10^{15} radians/sec. The single pulse breakdown at 7 atmospheres of argon was the most reproducible breakdown threshold obtained in the 10.6 micron experiments and was used for comparison with the optical frequency gas breakdown thresholds. Shown in Fig. 23 is the threshold power density for breakdown in 7 atmospheres of argon as a function of laser radiation frequency. To eliminate volume dependent effects (see Section C), the data of Fig 23 were all taken under conditions of equal focal volume. The dotted curve represents the dependence of threshold on frequency predicted by a cascade ionization process. The experimental threshold values vary approximately as the inverse square of the radiation frequency and for the radiation focal volume of the experiments, are in good agreement with the absolute values predicted by this theory for time limited loss-free breakdown. (see Section E).

Measurements of the breakdown threshold in high pressure argon with a series of pulses at a repetition rate of 150 pulses per second were also carried out. The threshold values obtained were identical to those measured with single pulses; establishing that, with a time interval of 7 milliseconds between pulses, the afterglow ionization of a breakdown plasma did not affect the threshold of subsequent breakdowns.

C. Focal Volume Dependence of Gas Breakdown at 10.6 Micron Wavelength

In the gas breakdown experiments at optical frequencies using ruby and neodymium laser radiation, it was observed that the threshold power density varied approximately inversely with the dimensions of the focal volume. In those experiments, the threshold power density required to generate breakdown for a focal diameter of 1.5×10^{-1} cm was over two orders of magnitude lower than the threshold for a focal diameter of 7×10^{-3} cm; the volume effect is therefore quite significant and appears to dominate the breakdown mechanism. Studies were undertaken to determine whether a similar effect is present for gas breakdown at 10.6 micron wavelength. As for the studies at optical frequencies,[5] the volume within which breakdown is produced was conveniently varied by using different focal length lenses to focus the laser radiation. The high pressure gas cell could not be used for the measurements of the breakdown threshold volume dependence because of mechanical problems of mounting the special short focal length lenses in the cell while maintaining a pressure seal. Experimentally, the threshold power required for gas breakdown in atmospheric pressure argon was greater than the 100-200 kilowatts available from the present CO_2 laser. Consequently, it was necessary to employ a Tesla spark preionization, as described above, in the vicinity of the focal region. The criterion for the breakdown threshold on these experiments was, then, the power density required for a certain number of breakdowns observed per minute with a laser pulse rate of 150 pulses per second. The fact that breakdown does not occur on every pulse is apparently determined by the random position of the Tesla spark streamers and the amount of preionization required for a given pulse amplitude to result in a cascade to breakdown. Even with the preionization assistance, breakdown in atmospheric argon could reproducibly be obtained only with two focal length lenses, giving the data shown in Table III.

Table III

Volume Dependence of 10.6 Micron Breakdown Threshold

lens focal length	number of breakdowns/min.	laser power density (watts/cm^2)
2.5 cm	1	1.8×10^8
2.5 cm	4	2.7×10^8
2.5 cm	7	2.0×10^8
2.5 cm	7	3.8×10^8
2.5 cm	26	1.0×10^9
2.5 cm	44	1.2×10^9
6.4 cm	1	1.3×10^8
6.4 cm	3	1.4×10^8
6.4 cm	5	1.8×10^8
6.4 cm	7	1.8×10^8

As can be seen from the table, regardless of the criterion for breakdown, i.e., the number of breakdowns per minute, the threshold power density decreases as the focal dimension (e.g., focal spot diameter = focal length x laser beam divergence) is increased. This result is the same as was observed for breakdown with optical frequency radiation, and it appears that the volume dependence of the gas breakdown threshold is not related to the wavelength of the radiation used.

D. Dependence of 10.6 Micron Radiation on Gas Species

With no preionization, breakdown in gases other than argon and xenon, whose thresholds were virtually identical, could not be produced even at pressures up to 10 atmospheres. As a result, to examine the difference in breakdown threshold at 10.6 microns for gases of different ionization potentials, the pulsed output of the Q-switched oscillator-amplifier laser was focused in the gases at atmospheric pressure, and a Tesla spark was used to preionize the gas as in the volume dependence experiments of Section C. For comparison with breakdown experiments at optical frequencies with ruby and neodymium radiation, the gases studied were argon and helium. Even with preionization, breakdown in air could not be produced with the laser power available. As a measure of the ionization cascade threshold, the number of breakdowns produced in a one minute time interval were recorded as a function of the focused 10.6 micron laser power density. The results obtained are tabulated in Table IV. In each case, the threshold for helium is higher than that of argon by a factor of approximately three. This is the same result as obtained at optical frequencies,[5] and, as in that case, is apparently due to the larger ionization potential and lower collision frequency of helium.

Table IV

Comparitive Breakdown Thresholds of Argon and Helium

Gas Species	Number of Breakdowns per min	Power Density (watts/cm^2)
argon	1	1.8×10^8
argon	4	2.7×10^6
argon	7	2.0×10^8
argon	7	3.8×10^8
argon	90	6.7×10^8
helium	0	6.8×10^8
helium	1	6.8×10^8
helium	2	7.6×10^8
helium	44	8.6×10^8

E. Cascade Breakdown Theory

The energy gain by free electrons in a gas oscillating in an ac radiation field has been treated by many authors with the result[21]

$$\frac{d\mathcal{E}}{dt} = \frac{e^2 PZ}{m(\omega^2+\nu_c^2)}\nu_c \qquad 4$$

where $\mathcal{E}$ is the electron energy, e is the electronic charge, m the electron mass, ν_c is the electron-atom collision frequency, ω is radian frequency of the field, P is the radiation power density, and Z is the impedance of free space. The energy gain in a collision is then

$$d\mathcal{E}_{coll} = \frac{1}{\nu_c}\frac{d\mathcal{E}}{dt} = \frac{e^2 PZ}{m(\omega^2+\nu_c^2)} \approx \frac{e^2 PZ}{m\omega^2} \qquad 5$$

since $\nu_c \ll \omega$ for the conditions of the breakdown experiments. The energy excursion in the radiation field, however, are much larger than $d\mathcal{E}_{coll}$ and are given aproximately by

$$\Delta\mathcal{E} = d\mathcal{E}_{coll}\, 2\sqrt{\frac{\mathcal{E}}{d\mathcal{E}_{coll}}} \qquad 6$$

From the results of Fig. 23, P/ω^2 and thus $d\mathcal{E}_{coll}$ is essentially constant over the entire range of the laser produced gas breakdown measurements. Numerically, for the conditions of the breakdown experiments, $d\mathcal{E}_{coll}$ is approximately 0.016eV and, assuming an average electron energy of ~3eV, $\Delta\mathcal{E}$ is about 0.4 eV. Since the energy excursions, $\Delta\mathcal{E}$, are small compared with the photon energy (~ 1eV) in the optical frequency breakdown experiments, the microwave picture is not directly applicable; quantum mechanical calculations for this case give algebraically the same result as Eq. 4, and this has been used to determine the theoretical pressure and frequency dependence of the optical frequency breakdown threshold. With 10.6 micron radiation, however, the energy excursions, $\Delta\mathcal{E}$, are large compared with the ~ 0.1 eV photon energy, and the classical theory certainly applies. For a cascade process, the electron density growth is exponential,

$$\frac{n}{n_o} = e^{\nu_i t} = e^{t/t_c}$$

where n is the time dependent electron density, n_o is the initial electron density produced by an independent process, e.g., photoionization at impurity atoms, ν_i is the cascade ionization rate and is equal to $d\mathcal{E}/dt$ divided by the atom ionization potential, and t_c is the e-folding time for electron growth.

Assuming that the initial ionization is such that only one electron is present within the focal volume, $n_o = 10^5$ cm^{-3}, and that complete ionization of the gas is produced in the breakdown, $N_T = 10^{19}$ cm^{-3},

$$\int_0^\infty \nu_i \, dt = \ln \frac{n}{n_o} = 33 \qquad 7$$

and

$$33I = \int_0^\infty \frac{e^2 p Z}{m(\omega^2 + \nu_c^2)} \nu_c \, dt \qquad 8$$

For a triangular shaped radiation pulse

$$P_t = 33 \frac{I m(\omega^2 + \nu_c^2)}{e^2 Z \nu_c} \frac{1}{T} \qquad 9$$

where P_t is the threshold radiation peak power and T is the laser pulse half width. For the conditions of the gas breakdown experiments, $\nu_c \ll \omega$, and

$$P_t = \left(\frac{33m}{Ze^2}\right) \frac{I\omega^2}{\nu_c} \frac{1}{T} \qquad 10$$

This simple model, although it neglects any loss processes and cannot account for the volume dependence of the breakdown threshold observed experimentally, does display the frequency (ω^2), species (I), and pressure (ν_c) variation of the threshold breakdown power. No theory has been developed which explains the threshold volume dependence, and this remains the major unsolved feature of the optical and infrared gas breakdown experiments.

F. Discussion

Gas breakdown studies with 10.6 micron wavelength radiation have been carried out using the output pulses of a Q-switched CO_2 laser. Because of the small photon energy 0.12 eV, associated with this radiation, multiple photon absorption effects and the quantum nature of the absorption process can be neglected, and the problem can be adequately described by a classical model. The simple model described in Section E shows the dependence of the gas breakdown threshold on the various experimental parameters and appears to describe the experimental results with the important exception of the focal volume dependence of the breakdown threshold.

The pressure variation of the breakdown threshold derives from the dependence of the energy absorbed on the electron-atom collision frequency. The electron-atom collision frequency is directly proportional to pressure, and at low pressures where $\nu_c << \omega$, the theory predicts a breakdown threshold inversely proportional to the gas pressure. From the data of Table II, this inverse dependence is observed experimentally for gas breakdown at 10.6 micron wavelength.

Using the data obtained previously with ruby and neodymium laser radiation and the data of this report at 10.6 micron wavelength, the frequency variation of the breakdown threshold of argon is plotted in Fig. 23. Both the experimental frequency dependency (solid line) and the threshold predicted by the cascade theory of Eq. 10 for a laser pulse width of 100 nanoseconds (dotted curve) are plotted on the Figure for comparison. The electron-argon collision frequency used for the calculations was for electron energies equal to one-third the ionization potential of argon, an energy considered representative of the average energy over the cascade. The agreement between the calculated thresholds and those determined experimentally is quite good for the focal volume of the data shown. However, the agreement in absolute value is observed only for the gas breakdown thresholds with small focal volumes. The theory does not account for the wide descrepancy which is present at large breakdown volumes.

The dependence of the breakdown threshold on gas species was studied using helium and argon. The 10.6 micron radiation was focused in the gases which were preionized by a Tesla spark. Based on the data of Table IV the ratio of argon breakdown threshold power density to that of helium is approximately 0.3. The cascade ionization theory predicts that the threshold power density is proportional to the ionization potential divided by the electron-atom collision frequency. Taking the collision frequency at an electron energy of 1/3 the ionization potential of the gas, the ratio of threshold powers for argon and helium predicted by the cascade theory is 0.28 in good agreement with the experimental observations. Experiments were also carried out examining the breakdown threshold in high pressure xenon. The ionization potential of xenon is lower than that of argon and the xenon collision cross section, and therefore collision frequency is higher. Consequently, the cascade theory predicts that xenon should be ionized more easily than argon. From the experimental measurements, however, the 10.6 micron breakdown threshold for argon and xenon are comparable. This result is in disagreement with the experiments using ruby and neodymium radiation and the cascade theory, both of which show a lower threshold for xenon. To determine the cause of this discrepancy, further investigations should be made of the breakdown threshold at 10.6 microns in xenon.

The gas breakdown threshold was observed to decrease with increasing lens focal length with the 10.6 micron wavelength radiation focused in a preionized gas. Because of the powers available, these studies were limited to lens focal lengths of 2.5 and 6.4 cm, and for this range the power density required for breakdown varies as $P \alpha \; (Dia)^{-.4}$. This variation of the breakdown threshold with initial breakdown volume is not explained by the cascade ionization theory. In the breakdown experiments with ruby and neodymium, an even more pronounced dependence of the threshold on focal volume was observed, and it appears, therefore, that the focal volume dependence is not limited to the optical frequency, large quantum, breakdown experiments.

Two mechanisms have been considered to explain the observed dependence at the breakdown threshold on focal volume. If a loss process which is related to the surface to volume ratio of the breakdown region occurs, this loss would be reduced as the dimensions of the focal volume are increased, and, as a consequence, the power density required for gas breakdown would be decreased. The presence of such a loss during the ionization cascade would require that the assumed energy absorption mechanism of cascade ionization be in error by as much as two orders of magnitude in the optical frequency experiments, and, from the data available, by a factor of two at 10.6 microns. However, it appears that the 10.6 micron breakdown can be adequately treated by a classical model, and should the volume dependence on the 10.6 micron experiments extend over any larger a range, it is difficult to imagine that the discrepancy lies in the calculated energy absorption. It is possible, however, that the calculated power density in the focal region does not represent the local power density in the experiments as a result of a mechanism which leads to an enhanced concentration of the radiation in the focal spot. While calculations of the condition required show that beam trapping in the gas does not occur, a phenomenon of this type may be required to explain the focal volume dependence of the gas breakdown threshold.

V. THIRTY-SIX MONTH STATUS EVALUATION

During the thirty-six months of this contract, the following specific objectives have been accomplished:

a. Studies of gas breakdown by optical frequency radiation have been carried out in argon, helium, neon, and air over the pressure range from atmospheric pressure to 1×10^5 torr using the $0.69\text{-}\mu$ and $1.06\text{-}\mu$ radiation from high-intensity ruby and neodymium lasers, respectively. With both ruby and neodymium radiation, breakdown in air was observed to require the highest field strength with successively lower field strengths required for the breakdown in neon, helium, and argon. At low pressures with either ruby or neodymium laser irradiation, the breakdown threshold was observed to decrease with pressure varying approximately as $1/\sqrt{P}$.

b. Measurements have been made of the attenuation of the incident giant laser pulse by the breakdown plasma. For beam intensities slightly above the breakdown threshold, it was observed with both ruby and neodymium radiation that more than half of the laser beam energy can be absorbed in the plasma produced by the breakdown and that over 90 per cent attenuation of the laser beam can occur during the later portions of the giant pulse. Measurements of the attenuation of an optical beam by the breakdown plasma at times following the incident giant pulse have been carried out using the cw beam from a helium-neon laser and show that the same 90 per cent attenuation is present for times of the order of milliseconds after the formation of the plasma. These measurements demonstrate the long-time effect of gas breakdown on the transmission of subsequent laser pulses.

c. Measurements have been made to examine the effects of diffusion-like losses on the breakdown threshold by varying the focal volume within which the breakdown is formed. The focal volume is characterized by the diffusion length, Λ, and studies have been made of the dependence of the breakdown threshold on Λ over the range 1.6×10^{-3} cm $\leq \Lambda \leq 3.0 \times 10^{-2}$ cm. With both ruby and neodymium radiation, the breakdown threshold for all of the gases studied is inversely related to Λ; i.e., breakdown within small focal volumes requires a larger optical frequency electric field than is necessary for larger volumes. These measurements have been carried out from atmospheric pressure to 1×10^5 torr, and at all pressures the same effect is noted. The dependence of the breakdown threshold on the dimensions of the breakdown volume implies that even at pressures as high as 1×10^5 torr, diffusion-like losses play a significant role in the deve opment of optical frequency breakdown and that the loss-free breal own threshold lies at still lower electric field strengths. F · the smaller focal vclumes, the threshold varies approximatel, as Λ^{-1}. While for the largest focal volumes studied the threshold varies as $\Lambda^{-1/2}$ showing a decrease in the volume dependence and indicating that the loss-free threshold is being apprcached.

d. In the experiments with neodymium irradiation, at the larger focal volumes with both helium and argon a pronounced minimum has been observed in the breakdown electric field vs. pressure curves. With ruby radiation no minimum is observed for helium and that for argon is less distinct and shifted to higher pressures.

e. Using the breakdown data obtained with ruby and neodymium laser irradiation, the frequency dependence of the breakdown threshold has been evaluated. For either argon, helium, or air the lower frequency neodymium radiation gives a lower breakdown threshold than for ruby at low pressures. At high pressures the neodymium breakdown threshold of helium approaches the ruby threshold, while in argon the neodymium threshold is even larger than obtained with ruby as a result of the minimum observed with neodymium. For air the ratio of the neodymium .o r·hy breakdown threshold remains approximately constant over the essure range studied.

f. Theoretical studies have been carried out which show that existing classical models of the breakdown process are not adequate to explain the phenomena observed at optical frequencies. Multiple-photon theories recently proposed are unable to predict the magnitude of the E field required for breakdown or the pressure and volume dependence obtained experimentally. Calculations of the inverse bremsstrahlung cascade theory of the breakdown process have been carried out for optical frequencies where the photon energy is greater than the classically calculated electron oscillation energy and show that an electron exchanges energy with the applied electromagnetic field in increments of the photon energy. This result differs in kind from that obtained using the classical microwave theory and offers an experimental test to examine the validity of the inverse bremsstrahlung model.

g. Measurements have been made of the breakdown threshold of mixtures of gases to study the effects of controlled impurities on the breakdown threshold. As little as 1 per cent neon added to argon reduces the breakdown threshold of the mixture to two-thi the threshold of argon alone. From the pressure and volume dependence of the breakdown, a model to explain the reduced optical frequency breakdown threshold of the argon-neon mixture has been constructed. From the results obtained, it appears, as first proposed by Zel'dovich and Raizer,[24] that excitation constitutes a loss process in the development of breakdown, and on the basis of the model of the gas mixture breakdown, radiative transport of this excitation energy from the breakdown volume is a diffusion-like loss process observed with the pure gases and the gas mixtures.

h. High-speed framing and streak photographs of the gas breakdown have been taken both during and after the giant laser pulse to determine the growth and lifetime of the breakdown plasmas. When initially formed, the plasma expands rapidly from its point of origin toward the incident laser beam at a velocity of 5×10^6 cm/sec. This rapid initial growth is followed by a slow contraction and a subsequent re-expansion accompanied by a decay of the breakdown luminosity. The transverse expansion of the breakdown is at all times slow compared to the initial rapid axial expansion, and after the termination of the laser pulse, the breakdown volume expands cylindrically with a diameter one-third its length. The breakdown volume has a long, narrow central core of high intensity which persists for times of the order of microseconds following the breakdown. Two theoretical models have been proposed to explain the rapid axial growth: (1) the energy-supported blast wave, where the laser energy is supplied to the existing breakdown plasma, and (2) breakdown propagation in which the laser beam intensity, increasing with time, becomes sufficiently high at successive points toward the incident laser beam to produce breakdown. In breakdown using large focal length lenses, the latter mechanism has been observed experimentally. Individual breakdowns are observed, separated in space and each propagating into the incident laser beam. The same mechanism may be involved in the short focal length breakdown propagation, but since the intensity decreases so rapidly away from the focal spot, the individual breakdowns are not observable.

i. Breakdown threshold measurements in cesium vapor at approximately 1 torr using ruby and neodymium laser radiation have been carried out to test the incremental photon absorptions predicted by the quantum mechanical inverse bremsstrahlung energy absorption mechanism. It was found that the ratio of the breakdown threshold power for cesium to that for argon is approximately 10 times less than that predicted by the classical microwave model of energy absorption. These results indicate that the rate of energy addition for a process requiring only 3 or 4 photon increments of energy is greater than that predicted for a many-step process. It was also determined experimentally that the breakdown thresholds of cesium vapor with ruby and neodymium laser radiation were approximately equal. This result shows that the cesium breakdown differs from that in the inert gases, since for the inert gases the threshold due to ruby radiation was twice that with neodymium radiation at atmospheric pressure, as predicted by the classical microwave model.

j. The breakdown threshold of argon with small added percentages of cesium vapor has been studied to determine the effects of impurities on the gas breakdown process. For atmospheric argon with a 10^{-3} torr cesium, the threshold power required to produce breakdown was reduced by a factor of two below that required for pure argon. The threshold reduction is due to ionization of the easily ionizable cesium and shows the importance of a low impurity level contamination on the breakdown process. Higher levels of cesium impurity (up to 1 torr) in atmospheric argon, while reducing the threshold of pure argon, did not result in as low a threshold as that determined with 10^{-3} torr cesium.

k. Breakdown produced by focusing the neodymium laser radiation in an argon electrical discharge was used to study the effects of an initial ionization on the breakdown process. Over the pressure range from 25 torr to atmospheric pressure, the breakdown threshold power required in the discharge was a factor of two less than that required for pure argon, the comparison for equal pressures. Based on the discharge voltage and current density, the electron density in the discharge was estimated to be in the range of 10^9 to 10^{11} cm^{-3}. The observed reduction in threshold with the initial ionization is consistent with the cascade growth of breakdown. In gas breakdown without the discharge, it is necessary for the ionization to grow from a very small initial ionization (most likely due to easily ionizable impurities) to full ionization of 10^{19} atoms cm^{-3} at atmospheric pressure. However, by starting with an initial electron concentration of 10^{11} cm^{-3}, the threshold power should be reduced by a factor of approximately two since one-half of the ionization generations necessary for full ionization have already been realized. The experimental observations further support the cascade growth process of gas breakdown.

l. The effects of the mode structure of the laser beam on the gas breakdown threshold have been investigated using laser pulses with two different mode structures: (1) temporally smooth multiple-mode neodymium laser pulses as used in previous experiments,[1-10] and (2) mode-locked pulses with well-defined intensity spikes caused by phase-locking of the laser cavity modes with a saturable dye Q-switch. With multiple mode lasers, interference between various modes in the focal region can lead to large localized electric fields which could be the cause of breakdown rather than the temporally and spatially averaged field strengths measured experimentally. The mode-locked laser pulses consist of a train of high-intensity short pulses, in which the peak intensities are several orders of magnitude larger than the average intensity of the pulse train. Despite the high-intensity fluctuations with the mode-locked pulses, the average power density required for breakdown with this pulse was found to be identical with that for the temporally smooth neodymium laser pulses. Based on this result, it is concluded that the breakdown threshold of gases by optical frequency radiation is independent of the mode structure of the laser radiation source, and the threshold is adequately described by the temporally and spatially averaged intensities measured experimentally.

These experimental measurements also show at optical frequencies that the multiple photon absorption process is not rate limiting in the development of gas breakdown. For the multiple photon process, the ionization rate is proportional to the joint probability of absorption of the n photons required to ionize an atom, and thus the ionization rate is proportional to the nth power of the radiation intensity. If the multiple photon theory were responsible for gas breakdown, slight variations in the laser beam intensity would produce large changes in the ionization rate and thus significant changes in the breakdown threshold. Since the intensity fluctuations with the mode-locked pulses did not materially affect the breakdown threshold, it is concluded that a multiple photon absorption process does not contribute to breakdown development.

m. Using a Mach-Zehnder interferometer, studies have been made of the growth and persistence of the breakdown plasma density and of the blast wave produced by gas breakdown. From the interferometric studies it was determined that the plasma is opaque to laser radiation for times as long as 100 nsec after breakdown. The attenuation of the He-Ne laser beam milliseconds after breakdown, described in paragraph b, is due to the turbulent heated gas in the breakdown region observed with the interferograms. At times 1-2 microseconds after breakdown initiation, the blast wave generated by the breakdown and observed in the interferograms is described by the Taylor strong blast wave theory.[19] The theory predicts the growth of the blast wave as $r = (\epsilon/\rho)^{1/5}\, t^{2/5}$ where r is the radial position at time t, ϵ is the absorbed laser energy, and ρ is the initial gas density, and describes the experimental blast wave position to within five per cent.

n. Investigations of the development of a high-power CO_2 laser with an output at 10.6 micron wavelength have been carried out. Investigations of optimum conditions for cw operation were undertaken and from a $2\frac{1}{2}$-meter long one-inch diameter electrical discharge laser, 125 watts of continuous power were obtained. A capacitor pulsed electrical discharge laser of the same length tube was also studied. Peak pulsed powers of over 700 watts were obtained from this system, showing that the pulsed excitation of the CO_2 laser is more efficient than the continuous discharge laser.

o. Passive Q-switching of the 10.6 micron CO_2 laser has been demonstrated. The saturable absorber used was propane gas contained in a gas cell internal to the laser cavity. At a propane pressure of one atmosphere, the laser output consisted of irregular pulsed outputs with intensities much greater than the cw power level. Pulses produced with a rotating mirror Q-switch were more reproducible and also gave higher peak powers. Consequently, the rotating mirror Q-switch instead of the bleachable gas system was used for the high-power oscillator-amplifier CO_2 laser.

p. Using a rotating mirror, the Q-switched operation of an electrical discharge CO_2 laser was investigated. Peak powers of 10 kilowatts were obtained from a Q-switched one-meter long oscillator. It was found that the dynamics of the relaxation of rotational and vibrational CO_2 levels are important in determining the maximum Q-switched peak powers that can be obtained from the CO_2 gas laser. With longer oscillator tubes, the effects of tube walls and the difficulty of mirror alignment limited the Q-switched power. The pulse from a Q-switched one-meter long oscillator was amplified by a second CO_2 discharge tube. Optimization of amplifier conditions resulted in power amplifications as high as 25, compared to the cw amplification of a factor of 5 for the 10-meter path-length amplifier. Peak powers of 2×10^5 watts have been obtained with this system.

q. Using the 200 kilowatt pulses from the Q-switched CO_2 oscillator-amplifier laser, gas breakdown at 10.6 micron wavelength has been achieved and the threshold power density for breakdown has been examined as a function of gas pressure, gas species, and focal volume. The threshold power density decreases inversely with argon gas pressure from 7 to 4 atmospheres. From measurements of breakdown in argon and helium, the threshold is directly proportional to the ionization potential divided by electron-atom collision frequency. Comparison of the threshold power density at 10.6 microns with that obtained using neodymium and ruby laser radiation extends the measurements of the frequency dependence of gas breakdown over a factor of ten in frequency. The agreement between the experimental values of the breakdown threshold and those predicted by the classical cascade theory is good. The breakdown threshold with the 10.6 micron radiation was studied as a function of the focal volume. The threshold was observed to decrease as the focal dimensions were increased, the same behavior as obtained at optical frequencies. Existing theoretical treatments of the gas breakdown development are unable to account for this phenomenon.

Measurements of the breakdown threshold in high pressure argon with a series of pulses at a repetition rate of 150 pulses per second were also carried out. The threshold values obtained were identical to those measured with single pulses, establishing that with a time interval of 7 milliseconds between pulses, the afterglow ionization of the breakdown plasma did not affect the threshold of subsequent breakdowns.

VI. REFERENCES

1. Meyerand, R. G., Jr. and A. F. Haught, "Research on the Electrical Breakdown of Gases under Intense Optical Illumination," Final Report, January 1964, C-920088-2, prepared under Conrract Nonr-4299(00) for the Office of Naval Research, January 1964.

2. Haught, A. F., "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semi-Annual Report, December 1964, C-920272-2, prepared under Contract Nonr-4699(00) for the Office of Naval Research, December 1964.

3. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semiannual Report, August 1965, D920272-4, prepared under Contract Nonr-4699(00) for the Office of Naval Research, August 1965.

4. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semiannual Report, January 1966, E920272-6, prepared under Contract Nonr-4696(00) for the Office of Naval Research, January 1966.

5. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Final Report, August 1966, E920272-8, prepared under Contract Nonr-4696(00) for the Office of Naval Research, August 1966.

6. Meyerand, R. G., Jr. and A. F. Haught, "Gas Breakdown at Optical Frequencies," Proceedings of the Sixth International Symposium on Ionization Phenomena in Gases, Paris, July 1963.

7. Meyerand, R. G., Jr. and A. F. Haught, "Gas Breakdown at Optical Frequencies," Physical Review Letters, Vol. 11, No. 9, November 1, 1963.

8. Meyerand, R. G., Jr. and A. F. Haught, "Optical-Energy Absorption and High-Density Plasma Production," Physical Review Letters, Vol. 13, No. 1, July 6, 1964.

9. Haught, A. F., Meyerand, R. G., Jr. and D. C. Smith, "Electrical Breakdown of Gases by Optical Frequency Radiation," Proceedings of Quantum Electronics Conference, P. L. Kelley, B. Lax, and P. E. Tannenwald (Eds.), McGraw-Hill Book Company, New York, 1966, p. 509.

10. Smith, D. C. and A. F. Haught, "Energy-Loss Processes in Optical Frequency Gas Breakdown," Physical Review Letters, Vol. 16, No. 24, June 13, 1966.

REFERENCES (CONT.)

11. Smith, D. C. and R. G. Tomlinson, "Effect of Mode Beating in Laser Produced Gas Breakdown," Applied Physics Letters, Vol. 11, No. 3, August, 1967.

12. Smith, D. C. and A. F. Haught, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semiannual Report, June, 1967, F920272-10, prepared under Contract Nonr-4696(00) for the Office of Naval Research, June, 1967.

13. Gill, D. H. and A. A. Dougal, "Breakdown Minima Due to Electron-Impact Ionization in Super-High-Pressure Gases Irradiated by a Focused Giant-Pulse Laser," Physical Review Letters, Vol. 15, No. 22, November 29, 1965.

14. Ehrlich, J. J., Hutcheson, G. J., Hales, W. L., and T. G. Roberts, "High-Power N_2HeCO_2 Laser Development," Journal of Quantum Electronics, Vol. QE-3, No. 6, June, 1967.

15. Dezenberg, G. J. and J. A. Merritt, "The Use of a Multipath Cell as a CO_2N_2 Gas Laser Amplifier and Oscillator," Journal of Quantum Electronics, Vol. QE-3, No. 6, June, 1967.

16. Kovacs, M. A., Flynn, G. W., and A. Javan, "Q-Switching of Molecular Laser Transitions," Applied Physics Letters, Vol. 8, No. 3, February 1, 1966.

17. Wood, O. R. and S. E. Schwarz, "Passive Q-Switching of a CO_2 Laser," Applied Physics Letters, Vol. 11, No. 3, August 1, 1967.

18. Flynn, G. W., Hocker, L. O., Javan, A., Kovacs, M. A. and C. K. Rhodes, "Progress and Applications of Q-Switching Techniques Using Molecular Gas Lasers," IEEE Journal of Quantum Electronics, Vol. QE-2, No. 9, September, 1966.

19. Hocker, L. O., Kovacs, M. A., Rhodes, C. K., Flynn, G. W., and A. Javan, "Vibrational Relaxation Measurements in CO_2 Using an Induced-Fluorescence Technique," Vol. 17, No. 5, August 1, 1966.

20. Wittke, J. P. and P. J. Warter, "Pulse Propagation in a Laser Amplifier," Journal of Applied Physics, Vol. 33, No. 6, June, 1964.

21. Brown, S. C., "High Frequency Gas-Discharge Breakdown," Technical Report 301, Research Laboratory of Electronics, Massachusetts Institute of Technology, July 25, 1955.

22. Alcock, A. J. and S. A. Ramsden, "Two Wavelength Interferometry of a Laser-Induced Spark in Air," Applied Physics Letters, Vol. 8, No. 8, April 15, 1966.

REFERENCES (CONT.)

23. Tomlinson, R. G., Damon, E. K. and H. T. Buscher, "The Breakdown of Noble and Atmospheric Gases by Ruby and Neodymium Laser Pulses," Proceedings of the Quantum Electronics Conference, P. L. Kelley, B. Lax, and P. E. Tannenwald (Eds.), McGraw-Hill Book Company, New York, 1966, p. 520.

24. Zel'dovich, Ya. B. and Yu. P. Raizer, "Cascade Ionization of a Gas by a Light Pulse," Soviet Physics JETP, Vol. 20, No. 3, March 1965.

VII. LIST OF FIGURES

ENERGY LEVEL DIAGRAM FOR N_2-CO_2 LASER

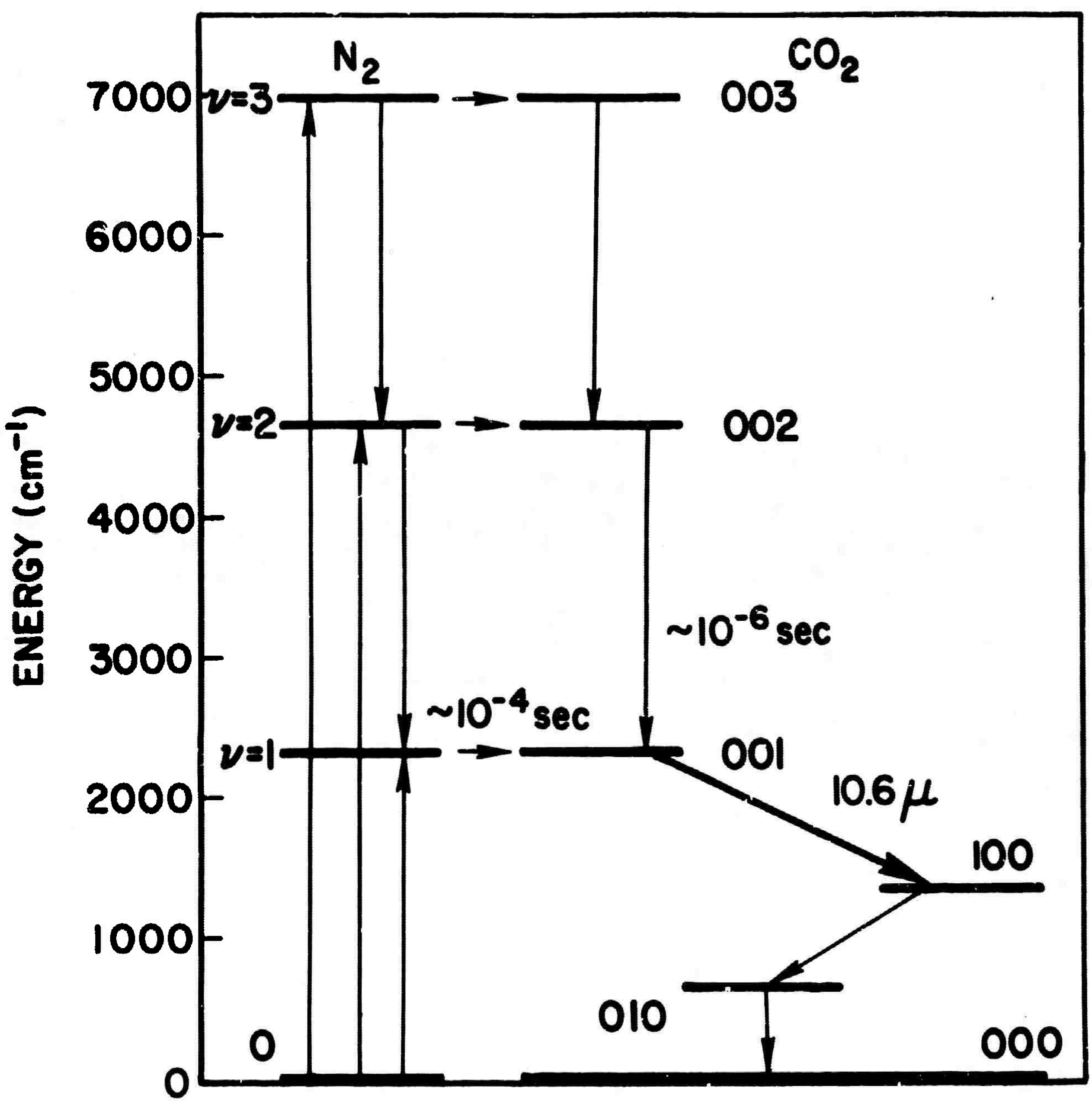

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FIG. 2

CO_2 LASER OSCILLATOR

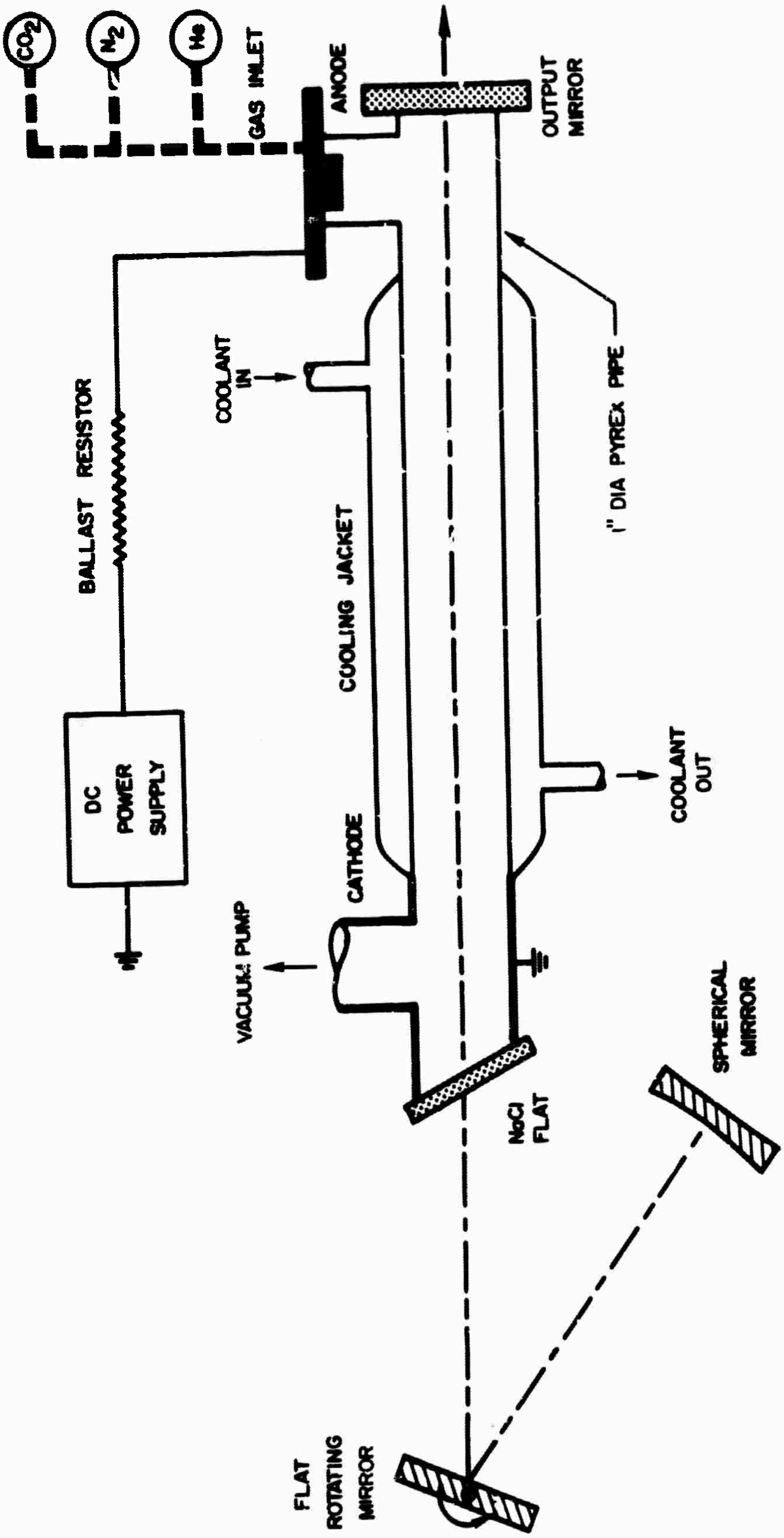

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FIG. 3

CW LASER POWER VS CO_2 PRESSURE

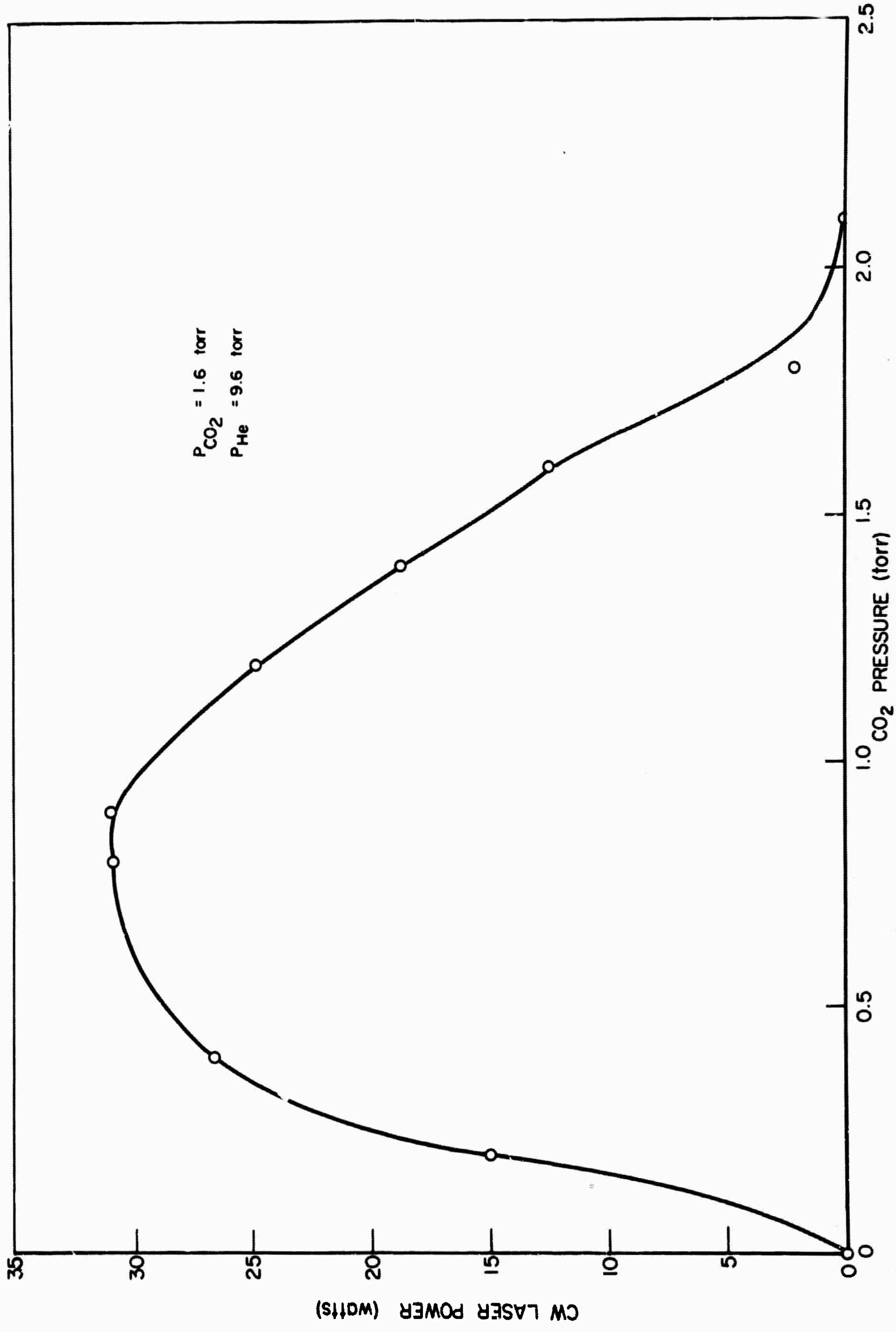

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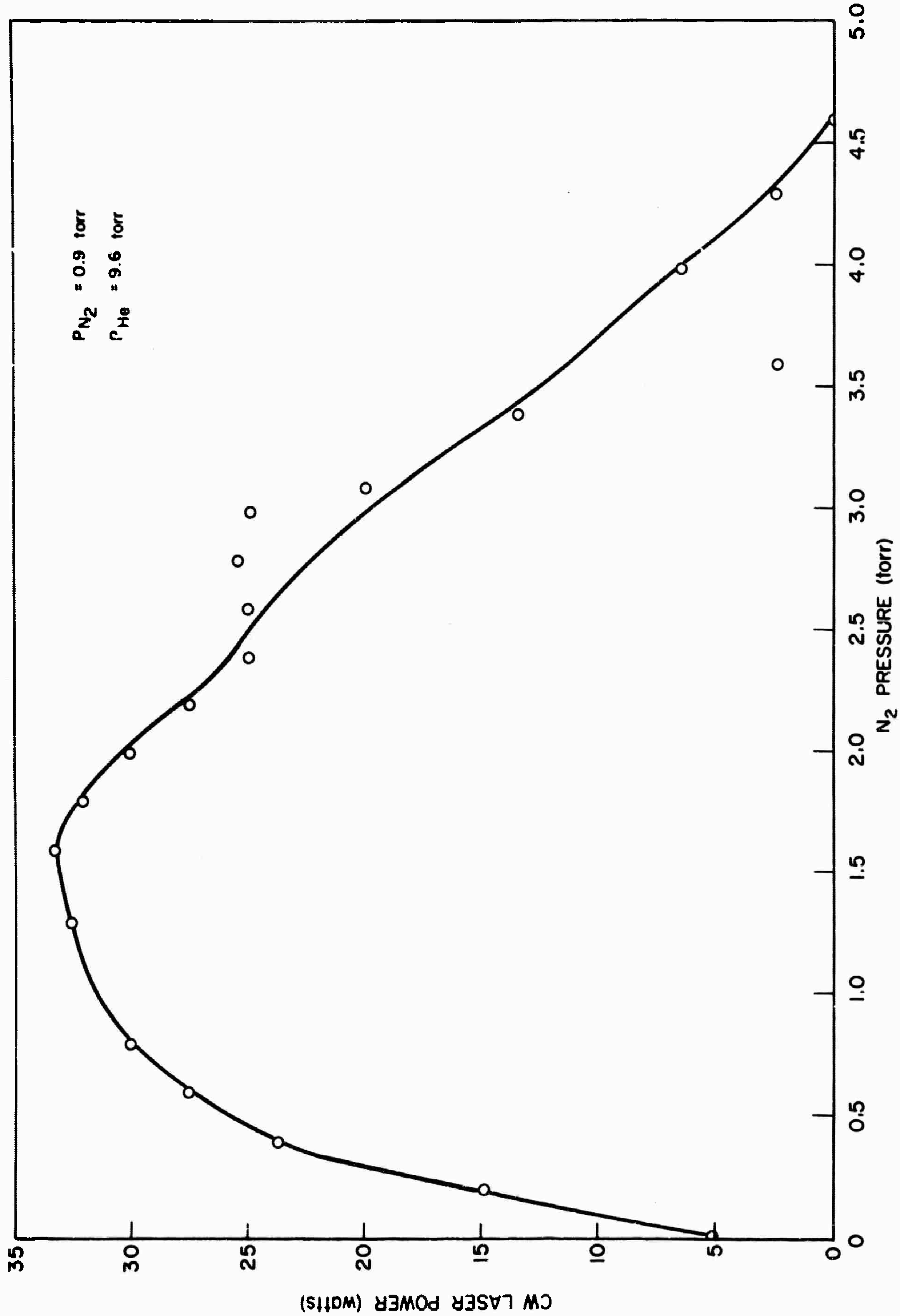
FIG. 4

CW LASER POWER VS N_2 PRESSURE



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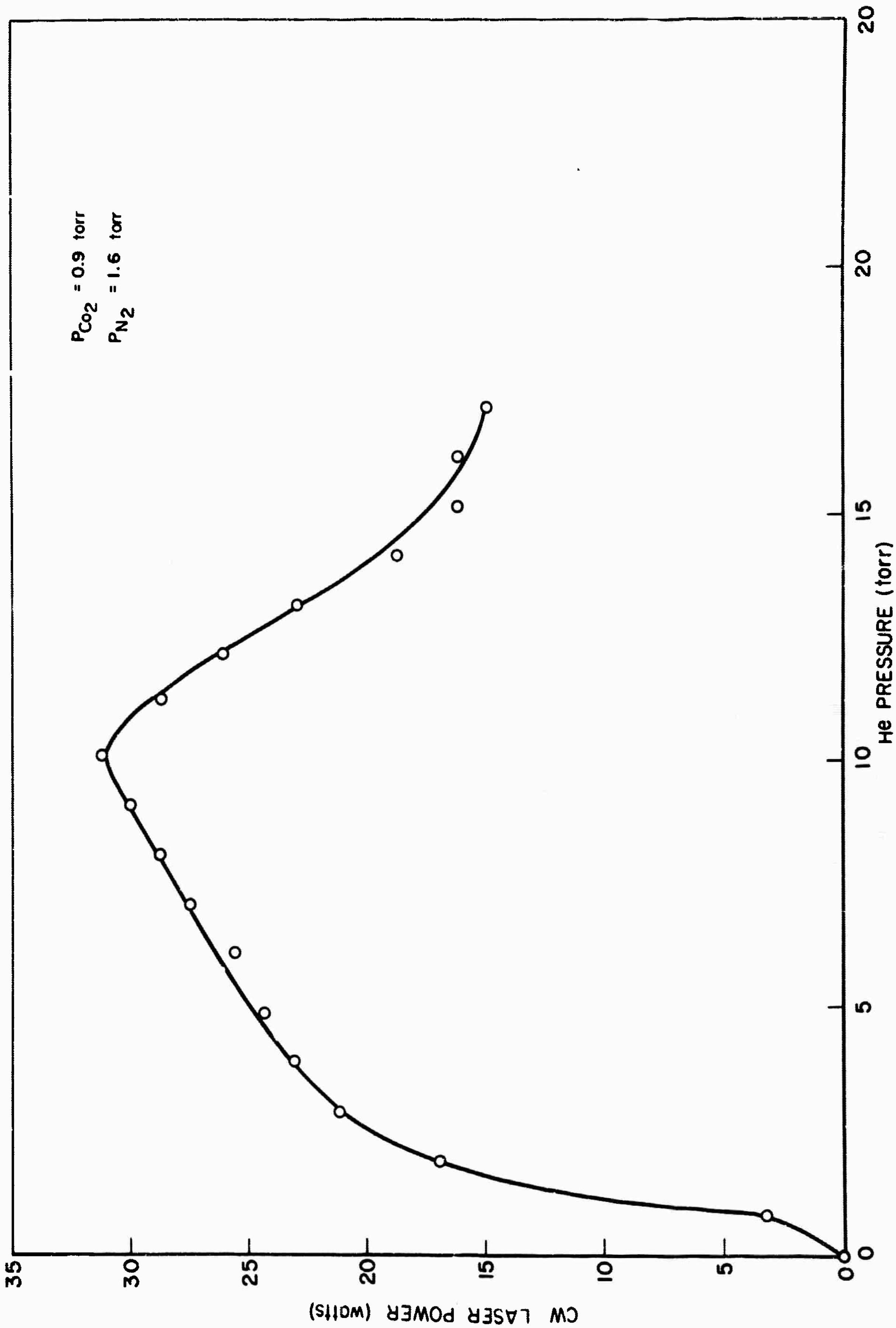

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FIG. 6

CW LASER POWER VS DISCHARGE CURRENT

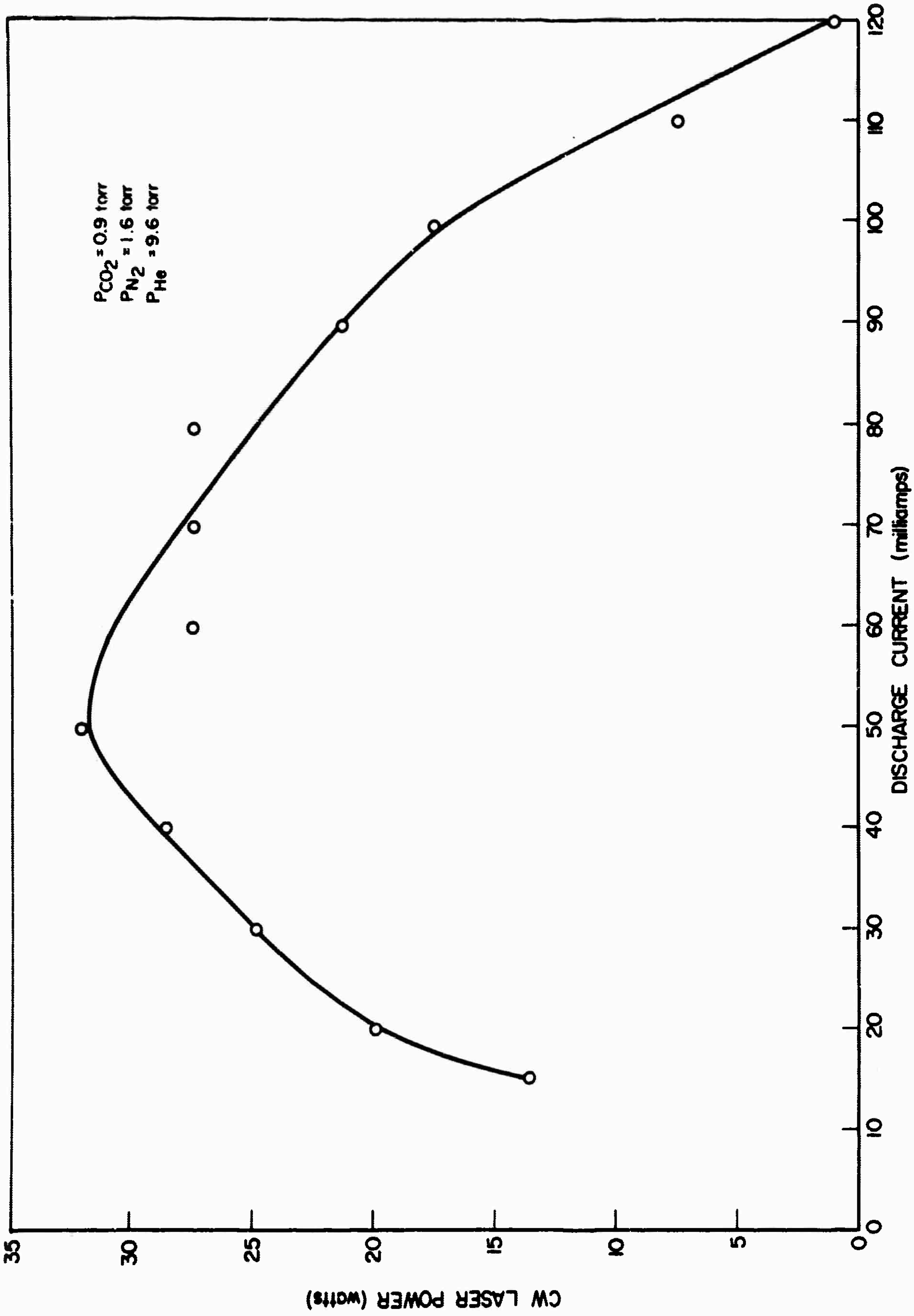

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FIG. 7

SCHEMATIC OF PULSED CO_2 LASER SYSTEM

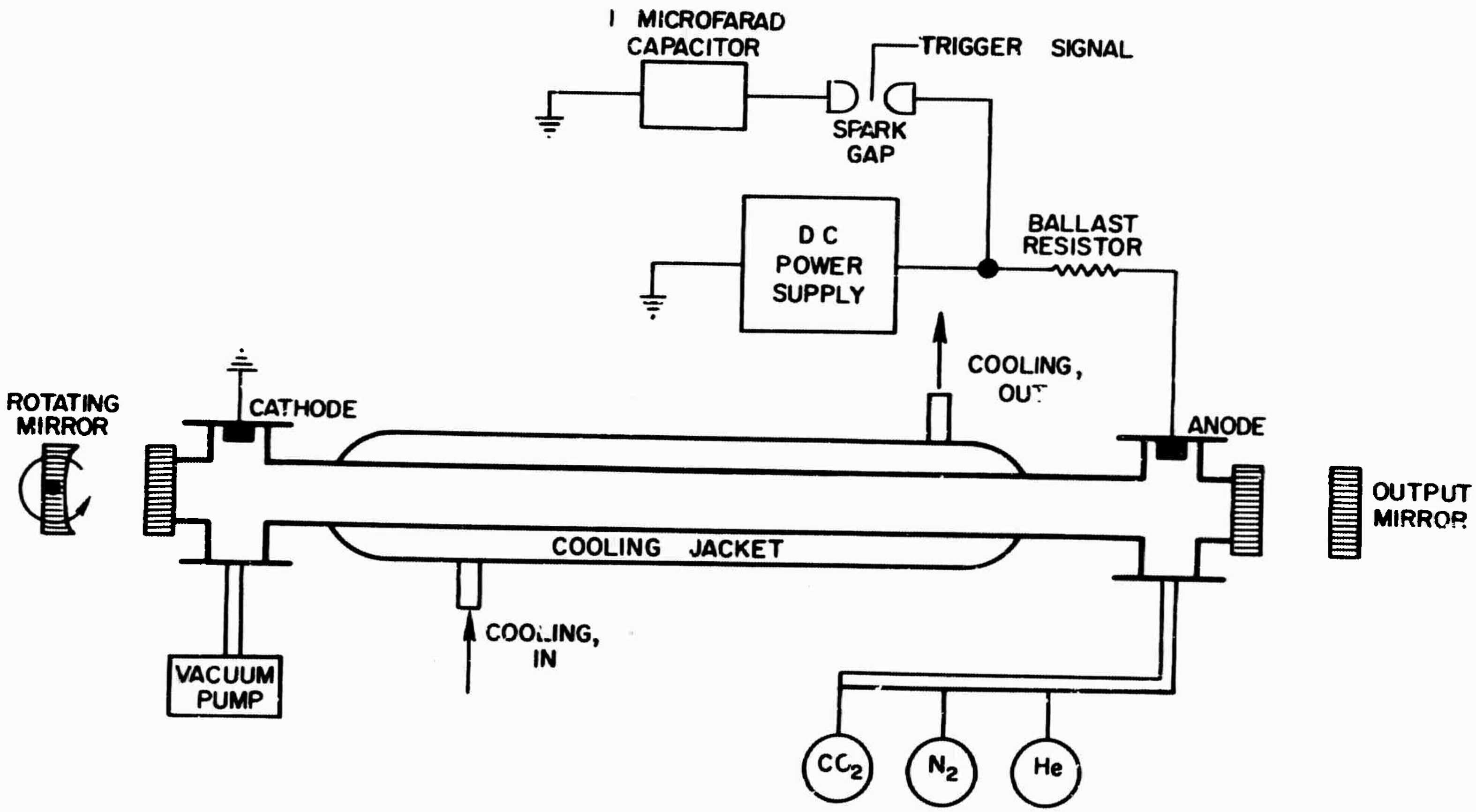
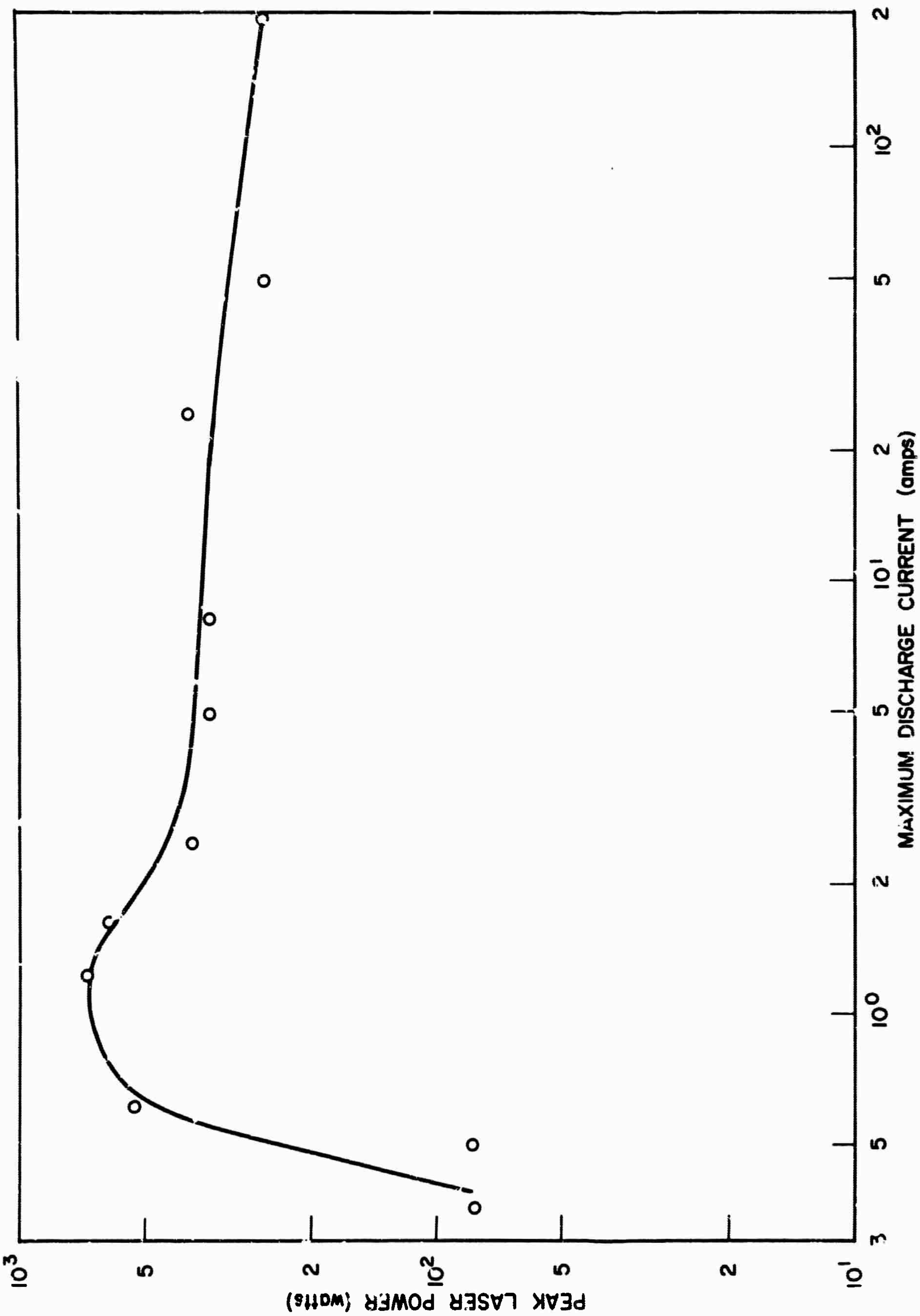


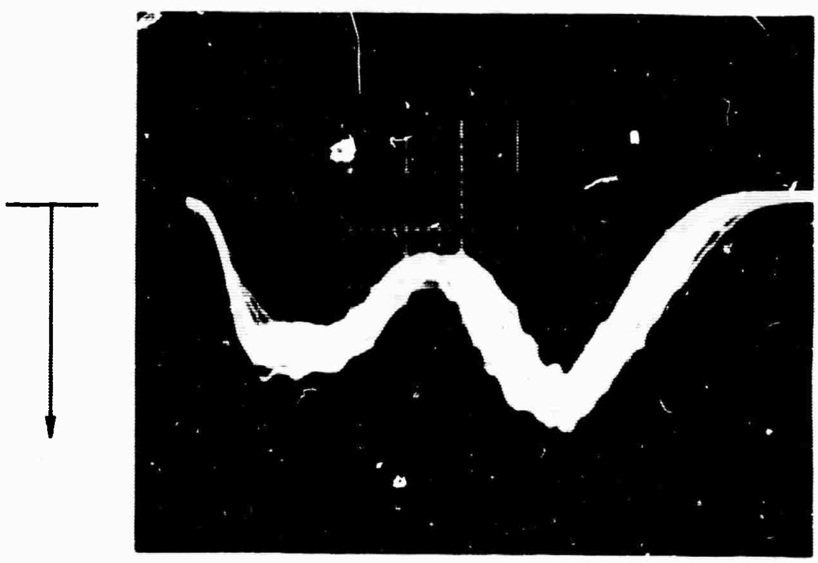
FIG. 8

PULSED CO_2 LASER POWER VS DISCHARGE CURRENT



Q-SWITCHED CO_2 LASER PULSE

INTENSITY



200 nsec /DIV

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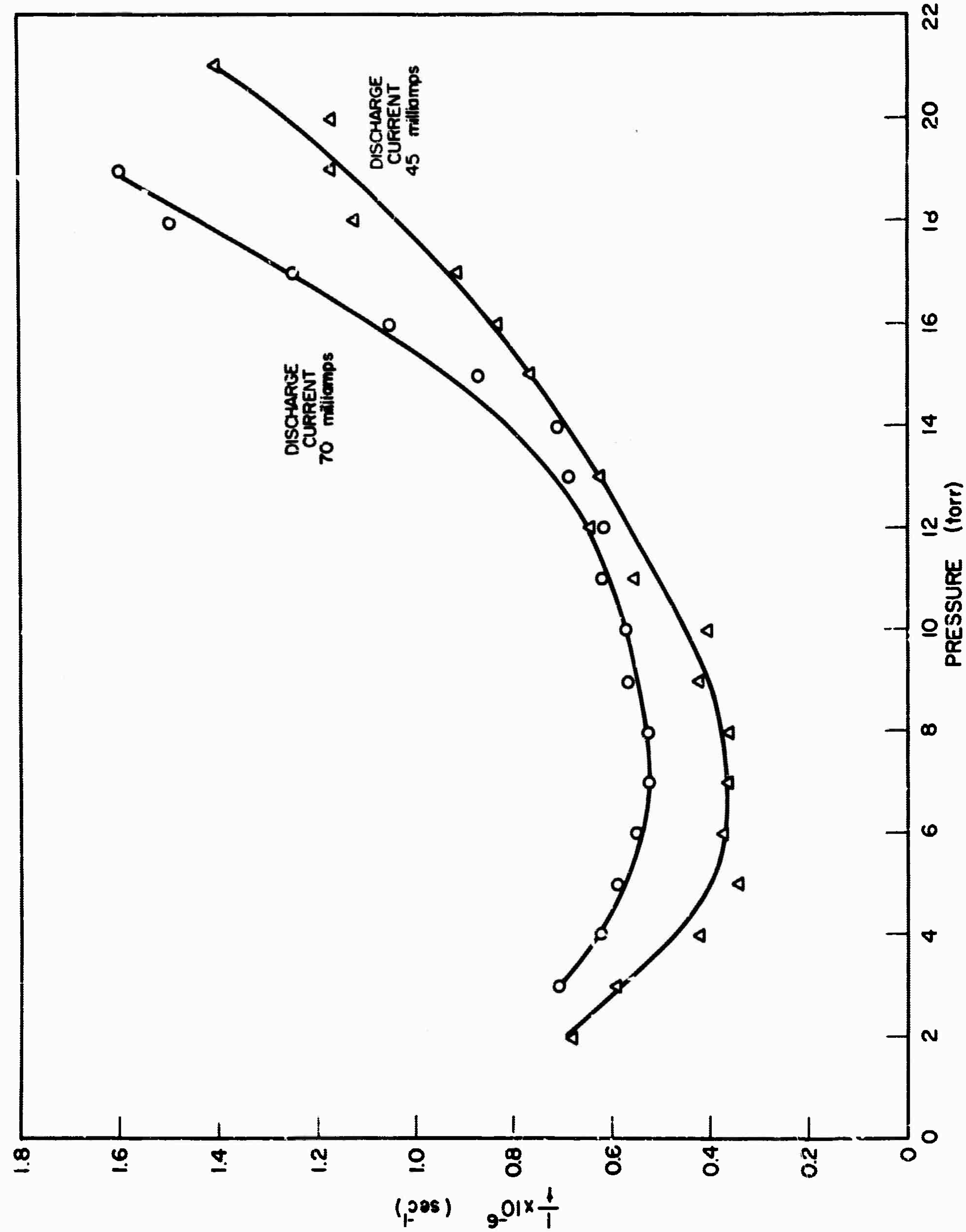
FIG. 10

TIME BETWEEN Q-SWITCHED PULSES VS DISCHARGE PRESSURE



Q-SWITCHED OSCILLATOR POWER VS CO_2 PARTIAL PRESSURE

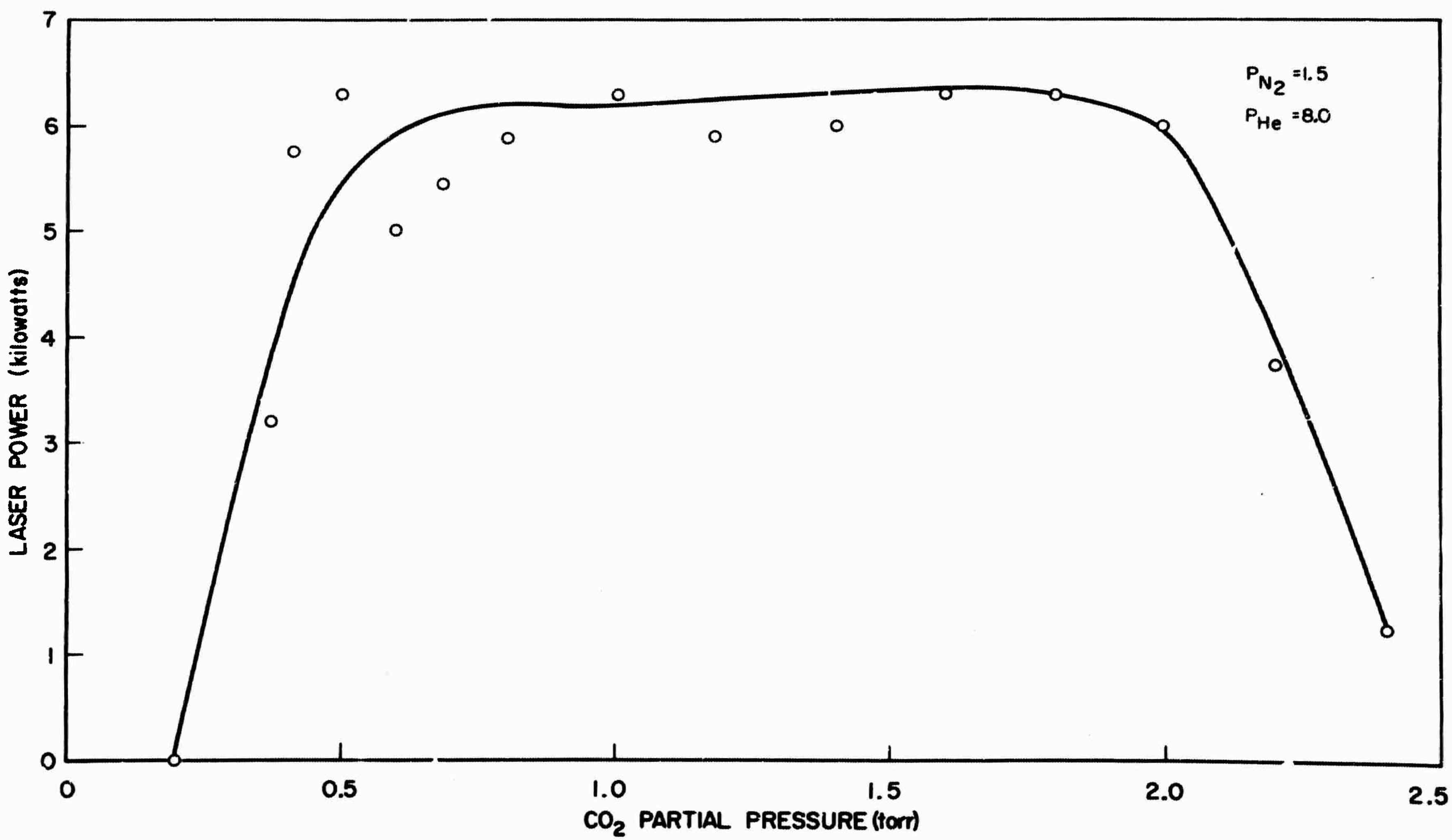


FIG. 11

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FIG. 12

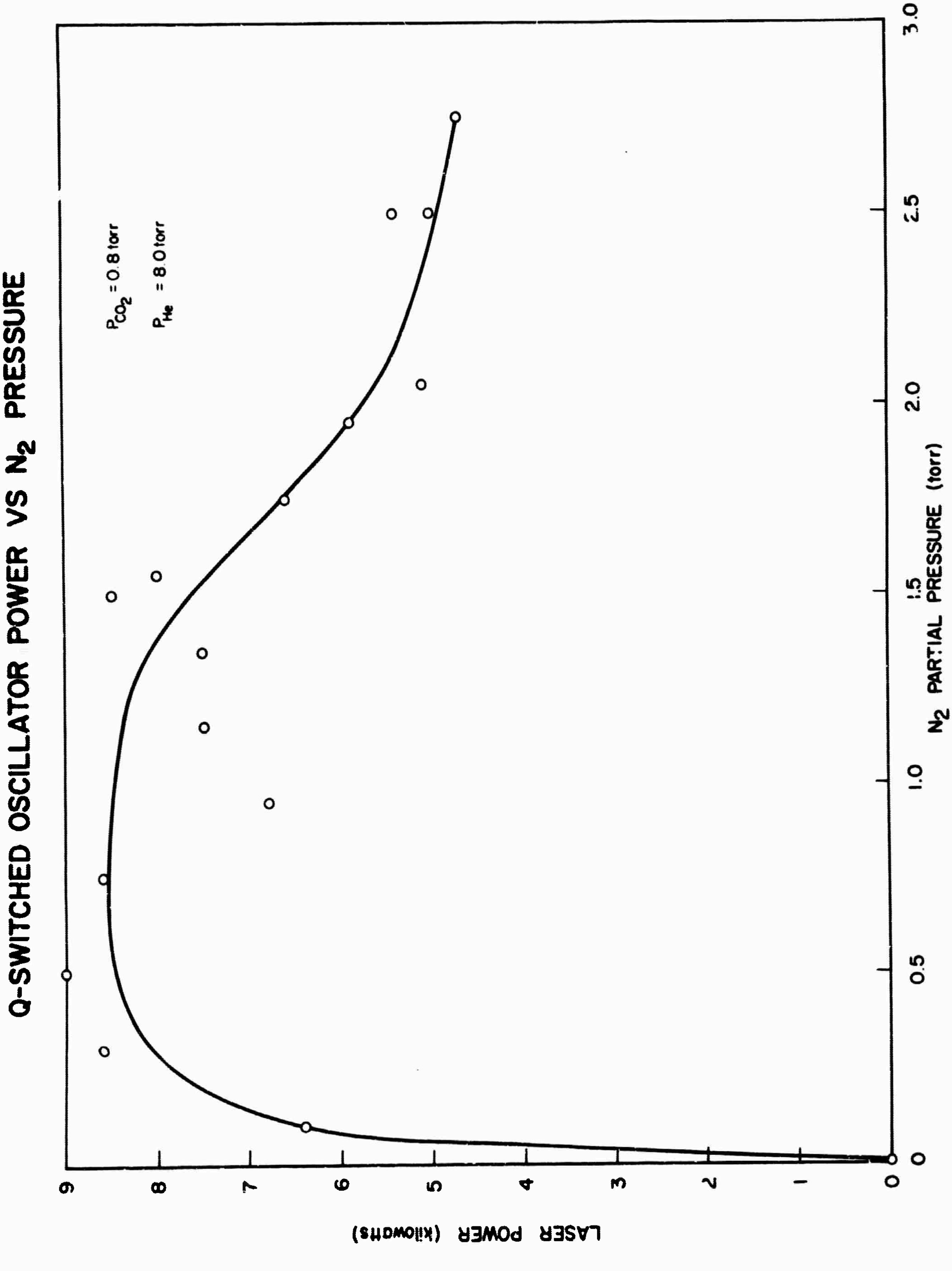

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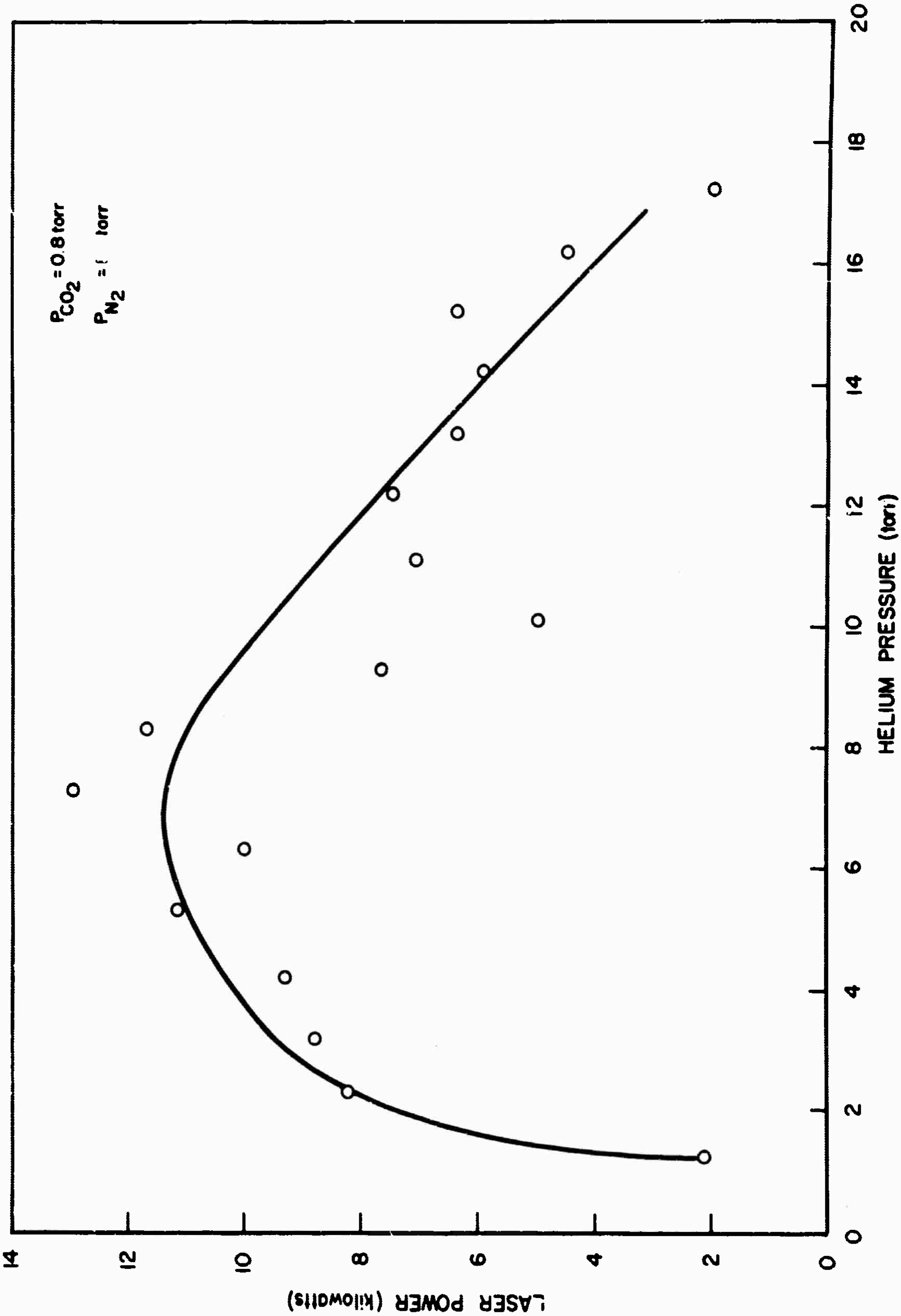
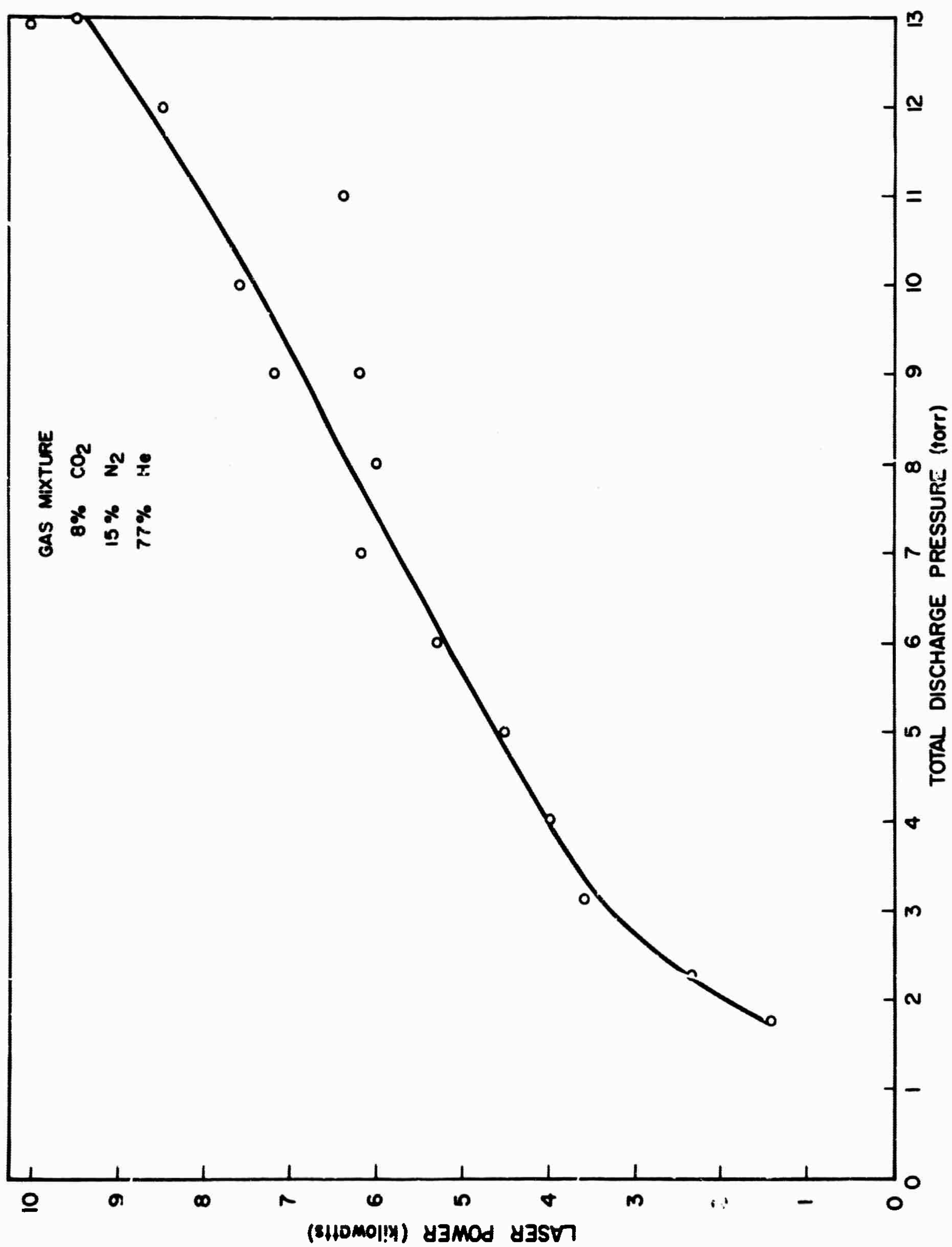
FIG. 13

Q-SWITCHED OSCILLATOR POWER VS He PRESSURE



F920272-12 FIG. 14

Q-SWITCHED OSCILLATOR POWER VS TOTAL PRESSURE



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CO_2 LASER OSCILLATOR AMPLIFIER SYSTEM

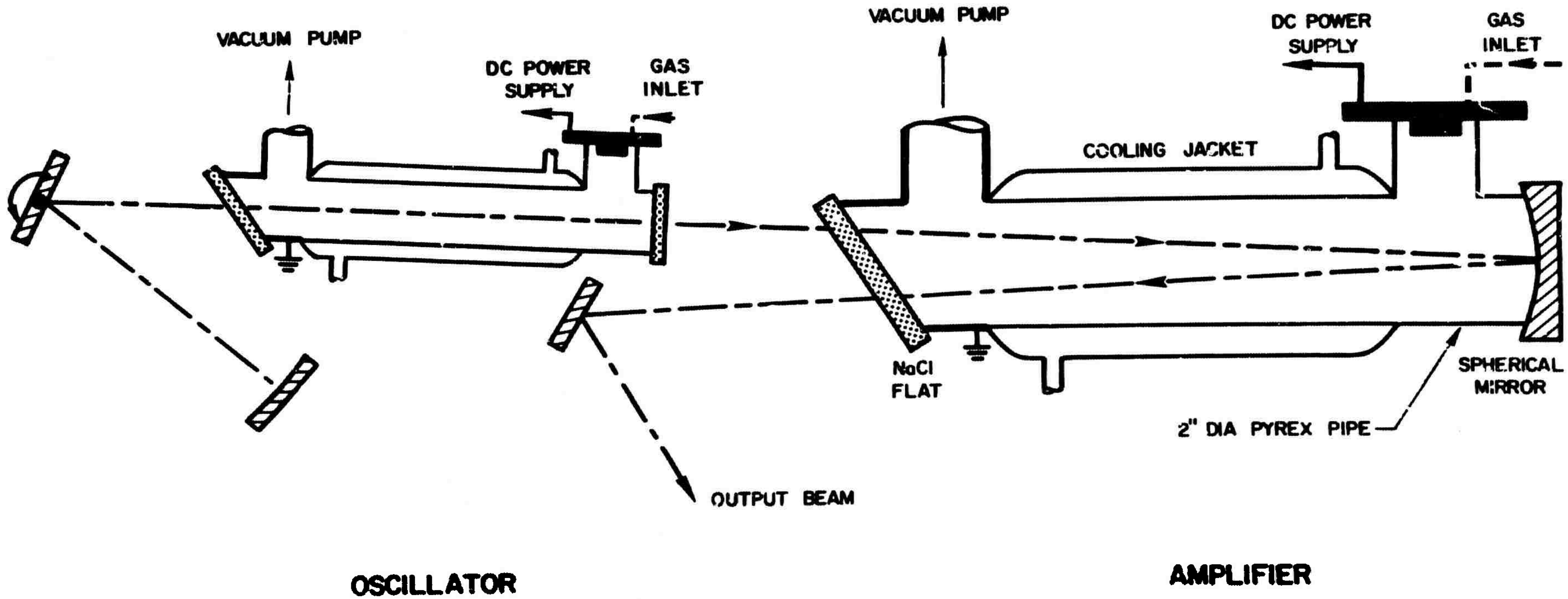
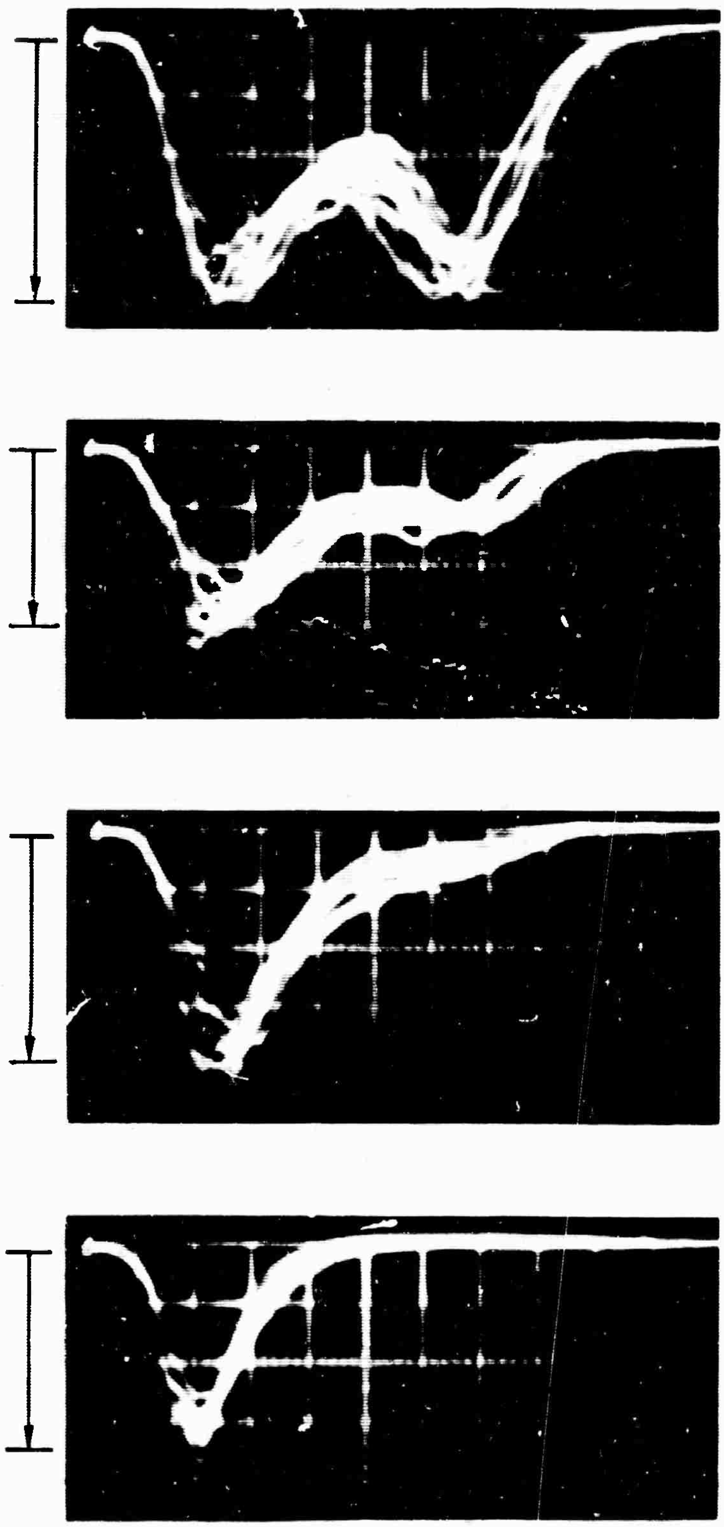


FIG.15

OUTPUT POWER VS AMPLIFIER PRESSURE



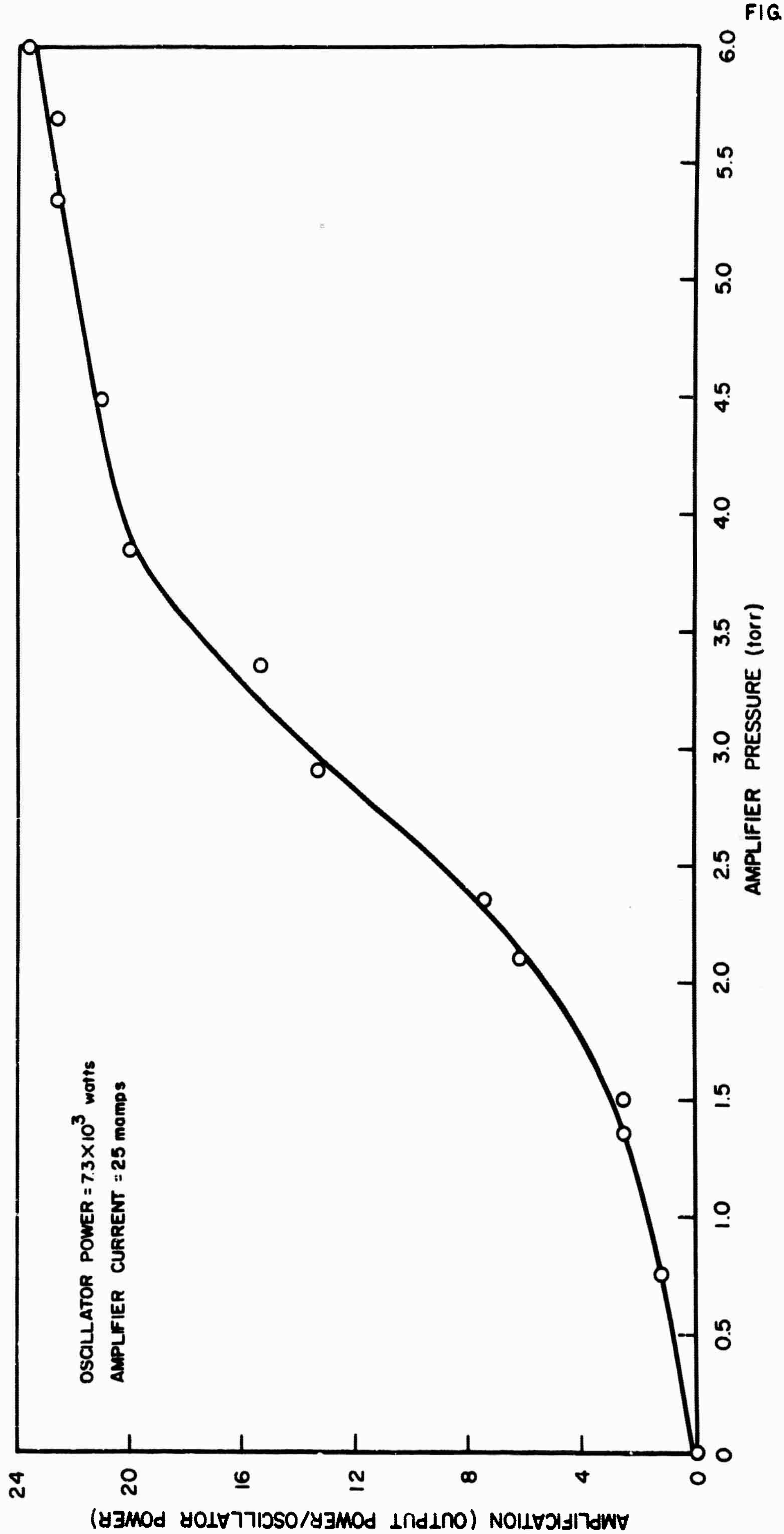
PEAK POWER (watts)	AMPLIFIER PRESSURE (torr)
7×10^3	0
1.8×10^4	1.4
4.5×10^4	2.1
1.6×10^5	5.4

100 nsec/DIV

F920272-12

FIG.17

Q-SWITCHED PULSE AMPLIFICATION VS TOTAL AMPLIFIER PRESSURE



Q-SWITCHED PULSE AMPLIFICATION VS CO_2 PRESSURE

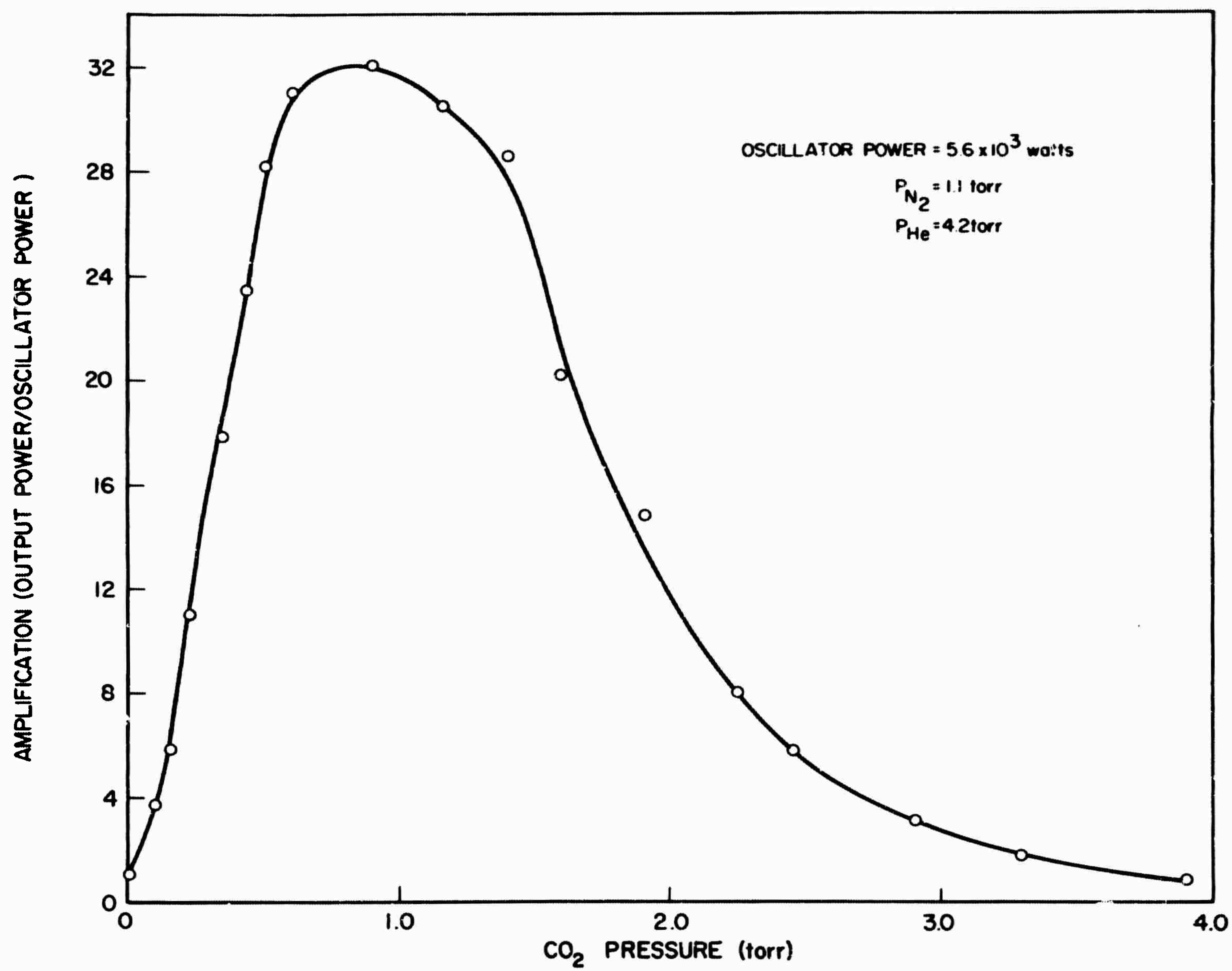
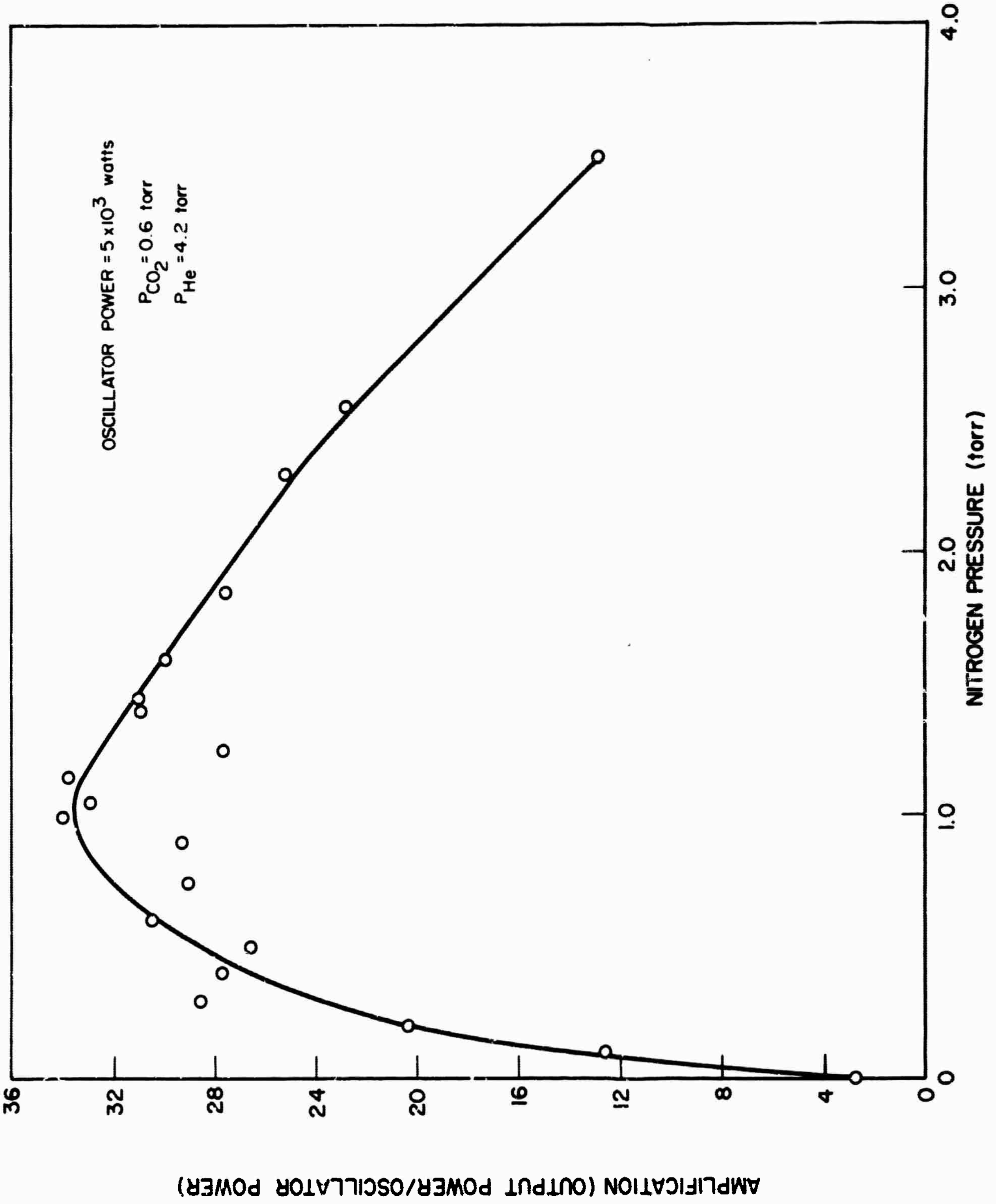


FIG. 18

F920272-12 FIG. 19

Q-SWITCHED PULSE AMPLIFICATION VS N_2 PRESSURE



Q-SWITCHED PULSE AMPLIFICATION VS He PRESSURE

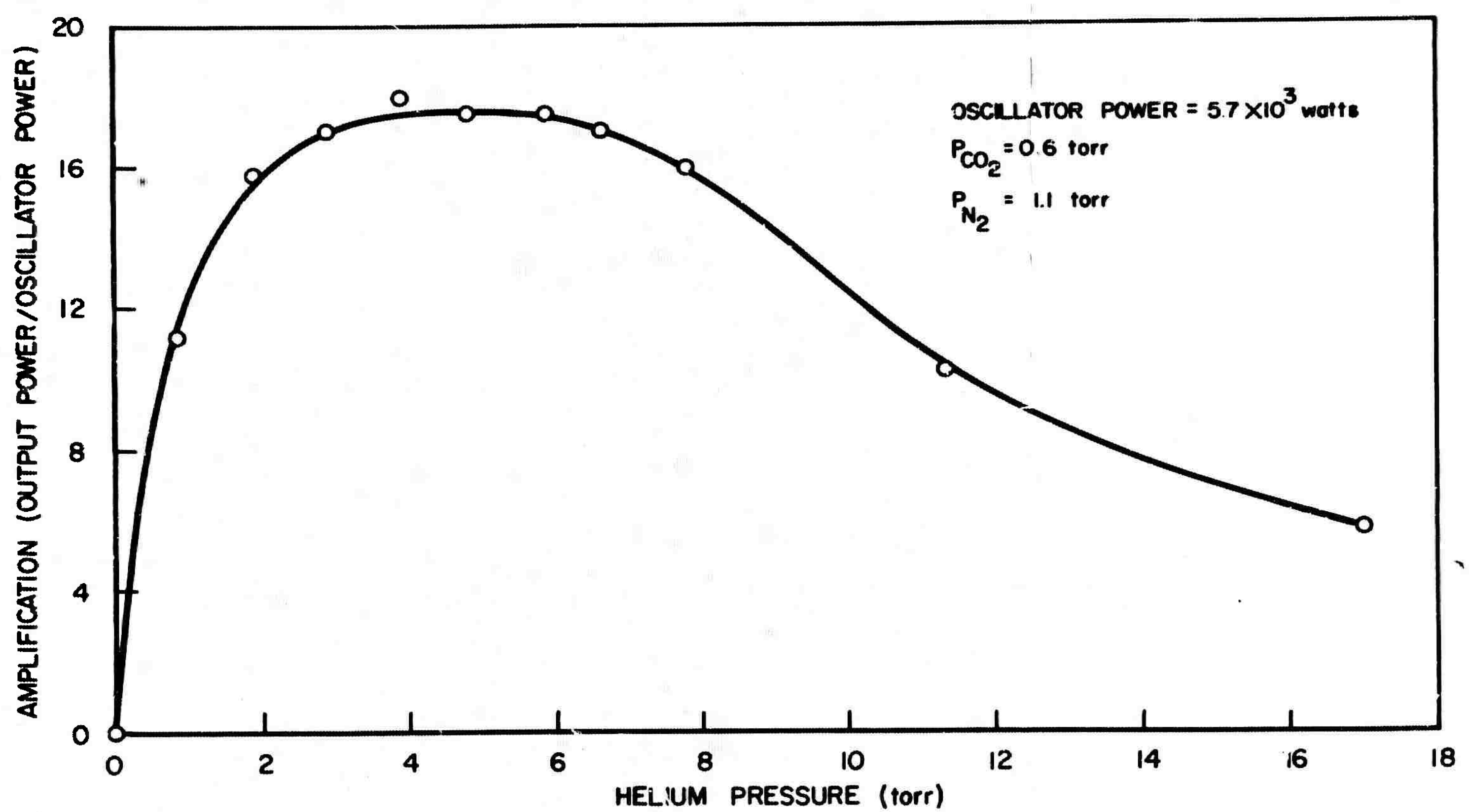


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FIG. 21

Q-SWITCHED PULSE AMPLIFICATION VS DISCHARGE CURRENT

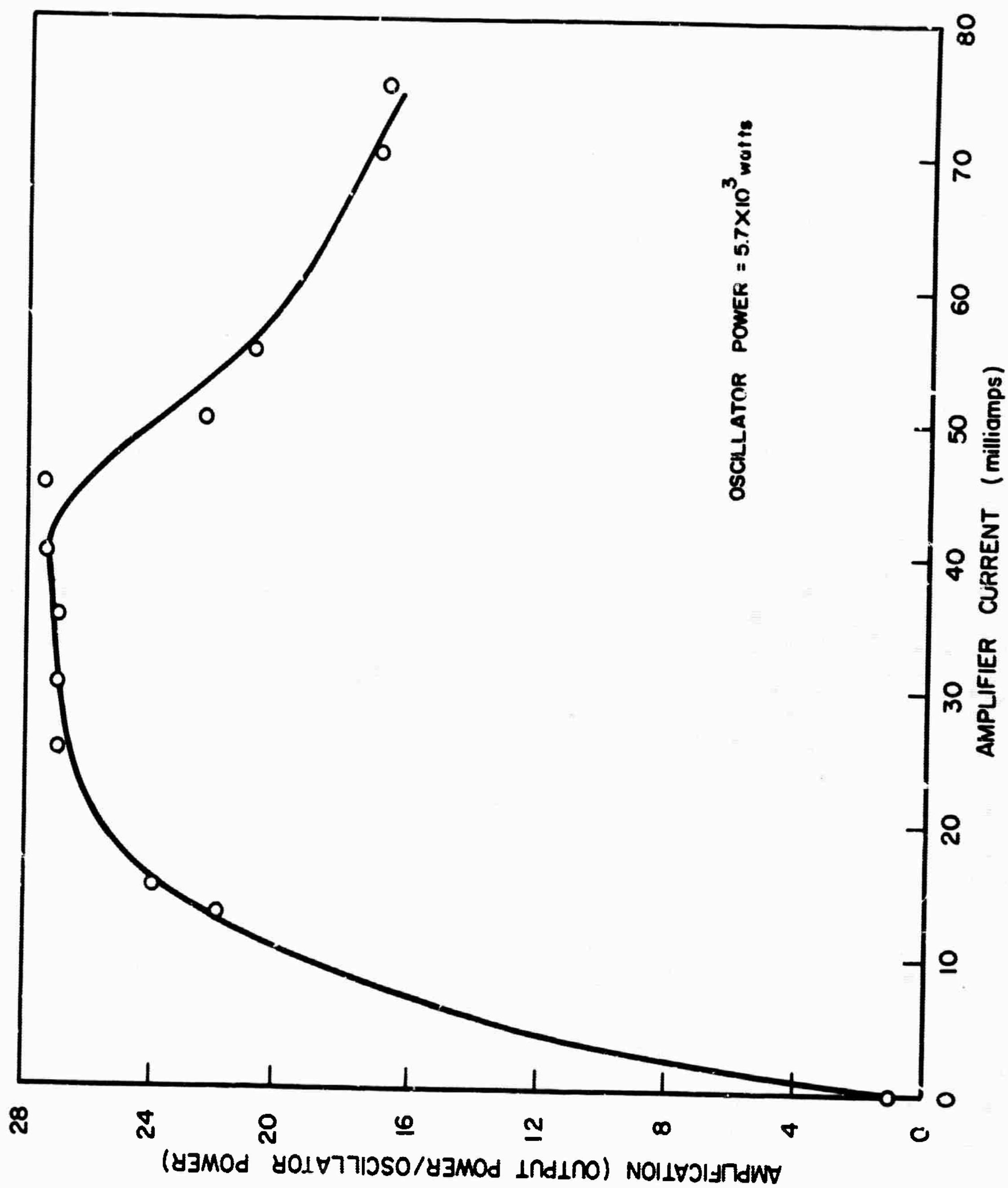

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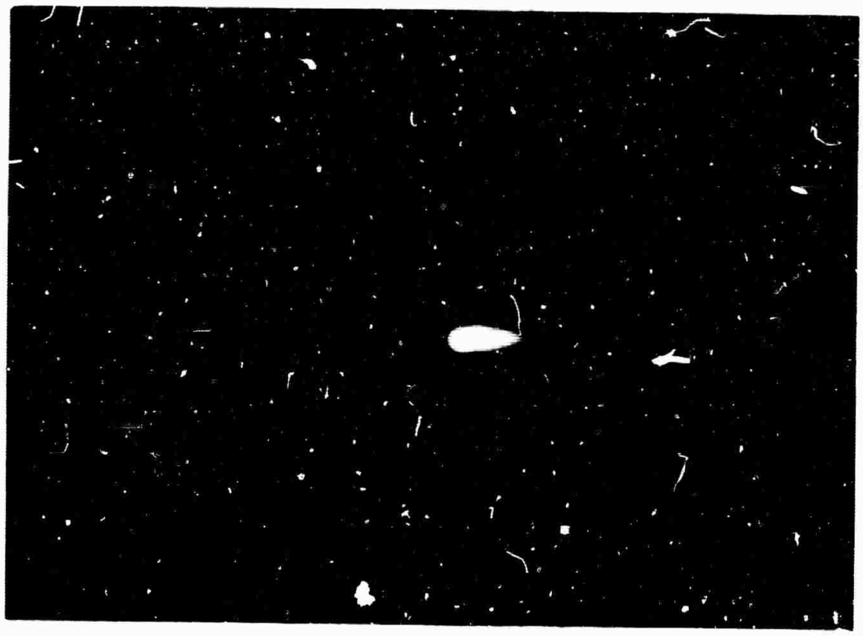
FIG. 22

GAS BREAKDOWN AT 10.6 MICRON WAVELENGTH

GAS BREAKDOWN – 6 atm ARGON



├— 1 cm —┤

LOW INTENSITY LUMINOSITY – 6 atm

├— 1 cm —┤

FREQUENCY DEPENDENCE OF GAS BREAKDOWN